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THE PRE-WISCONSIN DRIFT OF NORTH DAKOTA

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Considerably over one-half of North Dakota is covered by Wisconsin drift, which is found east of the Missouri plateau and also occupies a belt of country along the eastern margin of the plateau. The western border of the Wisconsin drift is marked by the wide, massive Altamont Moraine which crosses the state diagonally from northwest to southeast and has a width in places of 20 miles. West of this moraine there is an older drift sheet which extends from 70 to 130 miles beyond the Wisconsin drift and in North Dakota covers an area at the surface of approximately 19,000 square miles. The border of this older drift crosses the Montana boundary about 30 miles north of the Northern Pacific Railroad. This older drift undoubtedly underlies the Wisconsin drift of eastern North Dakota, but with possibly one exception it has not been observed in outcrops or recognized in wells.

East of the Missouri River the pre-Wisconsin drift, while covered in many places by outwash silt from the Altamont Moraine, is present in Emmons, Burleigh, eastern McLean and Mountrail, and perhaps in Williams and Divide counties. West of the Missouri River the older drift covers most of Morton, Dunn, and McKenzie counties, a corner of Stark, and all of Mercer and Oliver

counties. In this area west of the river outcrops are not uncommon, and thus the region is the most favorable in the state for the study of the older drift sheet.

The following account of some of the features of the pre-Wisconsin drift is based on observations made during the course of field work for the North Dakota Geological Survey, a portion of the time in co-operation with the United States Geological Survey, in Morton, Dunn, McKenzie, Burleigh, and other counties during the years 1909 to 1914 inclusive.

The older drift west of the Missouri is in most places thin and has undergone great erosion. The deposit perhaps never had any considerable thickness in this region except locally, where it forms moraines, and much of the glacial material which was formerly present has been swept away by streams. The drift throughout much of the area is thus represented by bowlders and gravel, the coarser materials left behind when the finer débris, such as clay and sand, was carried off. There are extensive tracts where little or no glacial material is present and where only an occasional bowlder or a patch of gravel indicates that the ice sheet once covered this region. The western margin of the older drift is therefore poorly defined, and the mapping of it is based largely on the distribution of glacial bowlders and gravel.

As would be expected from the foregoing characters, the pre-Wisconsin drift has not, except in certain restricted areas, affected the topography to any large extent. The region is one of many streams and mature drainage, in striking contrast with the area of the Wisconsin drift, with its few streams, numerous lakes, and youthful topography.

PRE-WISCONSIN DRIFT OF BURLEIGH COUNTY

East of the Missouri River in Burleigh County, between the river and the Altamont Moraine, the older drift is present, but the occasional outcrops appear to indicate that it forms only a thin veneer over the underlying rocks, seldom exceeding 8 or 10 feet in thickness. It outcrops in the bluffs of the Missouri River 3 miles northwest of Bismarck, where 10 feet of till is found, and in the cut at the east end of the Northern Pacific bridge it attains a thickness

of 15 to 20 feet. The bowlder clay appears in a number of the cuts along the Minneapolis, St. Paul & Sault Ste. Marie Railroad north of Bismarck, here generally associated with water-laid drift. It also outcrops at several points on Apple Creek, where it shows a thickness of 10–12 feet.

DRIFT IN MORTON COUNTY

West of the Missouri River in Morton County the glacial drift is represented almost wholly by gravel and bowlders, the latter occurring in great numbers. These bowlders, which are mostly granite, thickly cover the surface in many localities, resting directly on the bedrock, and except in rare instances no drift clay is associated with them. In some places they are scattered loosely over the ground, but in many others they form a bed or pavement in which the individual bowlders are in contact with each other. These bowlder deposits or bowlder beds are especially noticeable on the tops of divides and on upland areas. The bowlders vary in size from 6 or 8 inches to several feet in diameter, large ones measuring 8 and 10 feet being seen occasionally.

MORAINES OF LITTLE HEART RIVER BASIN

The most interesting and notable occurrence of glacial till in Morton County is found in the basin of the Little Heart River where the drift has been heaped up into morainic hills. During the Glacial Period this basin was probably occupied by an ice lobe of the continental glacier, and this lobe formed the belt of morainic hills which nearly encircles the broad valley plain and deposited more or less drift in the preglacial valleys of the Little Heart and its tributaries. As the ice

FIG. 1.—Bowlder-covered moraine hill of the pre-Wisconsin drift, Little Heart Basin, northeastern Morton County.

melted, the waters flowing from it deposited much outwash silt in the form of valley trains sloping away from the moraines. A number of the morainic hills have been partially buried by the outwash silt and rise like islands from the level plain of the valley train. The morainic belt of bowlder-covered hills and ridges is found near the base of the slopes on either side of the two valleys tributary to that of the Little Heart River (Fig. 1). Moraines cross the valley in three places and one belt of ridges and hills continues unbroken along the south side of the valley of the South Branch for a distance of 12 miles. The cultivated fields extend up to the moraine and end there where the soil becomes too rocky and the slopes too steep for cultivation.

FIG. 2.—Pre-Wisconsin till overlying Fort Union beds on Tobacco Garden Creek several miles above its mouth, McKenzie County.

FIG. 3.—Pre-Wisconsin till resting on stratified sand and gravel on Tobacco Garden Creek, near its mouth.

DRIFT IN MCKENZIE COUNTY

Near the western boundary of North Dakota the pre-Wisconsin ice sheet reached 35–40 miles south of the Missouri River and thus covered the greater part of McKenzie County which lies between the Yellowstone, Missouri, and Little Missouri rivers. The older drift left by this ice sheet is well shown in many places in this

region and the glacier also caused important drainage changes. The best exposures are found on Sand Creek, a short tributary of the Missouri River several miles east of Tobacco Garden Creek, on Tobacco Garden Creek, and on Clear Creek, a tributary of the latter.

FIG. 4.—Pre-Wisconsin drift resting on Fort Union sandstone, valley of Clear Creek, a tributary of Tobacco Garden Creek, northeastern McKenzie County.

Near the mouth of Tobacco Garden Creek appears 58 feet of till in a cut bank. It is yellowish gray or drab in color, contains many small bowlders, and rests on Fort Union beds (Fig. 2). Not far from here is seen 18 feet of bowlder clay overlying 15 feet of well-stratified sand and gravel (Fig. 3).

FIG. 5.—Pre-Wisconsin drift exposed on the tributary of Sand Creek, northeastern McKenzie County.

The valley of Clear Creek was partly filled with drift and there are many good outcrops of bowlder clay in the frequent cut banks along the stream where from 30 to 40 feet and over of till is exposed (Fig. 4). The greatest thickness found along this creek was in Sec. 36, T. 152 N., R. 97 W., where in a high bluff 100 feet of dark gray till overlies 100 feet of soft Fort Union sandstone. This outcrop lies within the morainic area to

be described later, which probably accounts for the exceptional thickness of the pre-Wisconsin drift at this point.

Another excellent drift section occurs in this same morainic area 3 miles west and one-half mile south of Charlson, or 5 miles south of the Missouri River on a tributary of Sand Creek (Fig. 5). Here the following section appears in the steep bluff which rises abruptly from creek-level:

	Ft.	In.
Sandy clay and soil	2	
Sand and clay in alternating bands	8	
Gravel		8
Sand and clay in alternating layers	3	
Gravel, coarse		8
Sand	2	4
Gravel	7	8
Till or bowlder clay, dark gray in color, and containing large numbers of pebbles and bowlders imbedded in the tough, hard clay. A large proportion of the bowlders and pebbles are composed of compact limestone and the till contains considerable blue shale (Pierre ?). Thickness of till exposed above the creek	61	
	85	4

The sand and gravel forming the stratified drift of the foregoing section are light yellow in color. The drift hills just back of the bluff rise 50–60 feet above the top of section, so that the total thickness of the drift above creek-level is from 140 to 150 feet.

BOWLDER BED ON THE MISSOURI RIVER

An interesting bowlder deposit belonging to the pre-Wisconsin drift is found along the Missouri River just above water-level, 2 miles below the Nesson Ferry and one-half mile below the mouth of Tobacco Garden Creek (Fig. 6). This bed of bowlders shows a thickness, above the normal stage of the river, of 12–14 feet and its depth below water-level was not determined. The deposit is well exposed along the water's edge for a distance of nearly 100 yards, and scattered bowlders and ferruginous gravel occur at intervals for another 200 yards. Overlying the bowlders is 15 feet of gravel, which is overlain in turn by silt and fine sand extending to the top of the terrace, 100 feet above the river. The bowlder

bed is composed of bowlders of all sizes, those from 2 to 3 feet in diameter being quite common, though those less than 1 foot in diameter are most abundant. One sandstone bowlder measured 14 feet in length, another was 9 feet long, and another 4 feet. Granite, limestone, petrified wood, and sandstone bowlders are found, together with other kinds of rock. The interstices between the coarser materials are filled with gravel and sand, and the whole deposit is cemented into a rather firm, indurated mass. It is very ferruginous and brown from the limonite forming the cementing material, and in many places the bowlders are firmly held by the iron cement and sand, which serve as a matrix in which the bowlders are imbedded; when the latter weather out their shape is preserved in the matrix.

FIG. 6.—Bowlder bed on the Missouri River near mouth of Tobacco Garden Creek, McKenzie County.

While some of the bowlders of this deposit may have been brought here by floating ice, it is probable that most of the deposit was left here by the pre-Wisconsin ice sheet when it advanced south of the river. The finer materials of the drift, if they were ever present, have been carried away, leaving the gravel and bowlders, which were subsequently cemented by the iron of the surface waters.

MORAINE OF THE PRE-WISCONSIN DRIFT

Mention has been made on a previous page of the moraines of the Little Heart River Basin, and in McKenzie County a much more extensive moraine of the pre-Wisconsin drift forms a prominent topographic feature of the region. It lies in the northeastern part of the county, east of Tobacco Garden Creek, where it extends on the upland from the edge of the Missouri Valley bluffs north

of Charlson in a southwesterly direction to the valley of Timber Prong Creek in Secs. 14 and 15, T. 151 N., R. 97 W. It has a length of 16 miles, an average width of 2 miles, and its area is about 30 square miles. This moraine shows well from Charlson, where its ridges and hills are seen rising from 100 to 150 feet above the flat plain in the foreground (Fig. 7). Within the morainic area the surface is rough and hilly and the ground is thickly strewn with bowlders. The topography is typically morainic, with numerous irregular hills and ridges, while scattered among the hills are great numbers of hollows or kettle-holes, some containing water and others dry. Many of the hills rise 50–125 feet above the bottom of the kettle-holes.

FIG. 7.—Small lake in the moraine of the pre-Wisconsin drift near Charlson, northeastern McKenzie County.

Where this moraine crosses the valley of Timber Prong Creek it forms a dam, which holds back the waters of the upper valley and forms a lake known locally as Dimick Lake. This moraine lake is very irregular in shape and has an area of between two and three square miles.

North of the Missouri River another morainic belt occurs which may be part of the pre-Wisconsin moraine just described as extending southwest from the vicinity of Charlson, though it is perhaps more likely to have been formed by the Earlier Wisconsin ice sheet referred to on another page. It lies from 2–3 miles west of White Earth Creek and with a width of 1–2 miles extends north and south a distance of at least 6 or 8 miles between the Missouri River and the Great Northern Railroad. Fifteen or 20 miles or more west of the Altamont Moraine the railroad crosses a well-developed moraine extending 4 or 5 miles and perhaps more north and south of Temple, and has a width of several miles. This hilly belt lies about 9 miles west of the above-mentioned moraine near White Earth Creek.

CHARACTERISTICS OF THE PRE-WISCONSIN DRIFT

The topography of the older drift and the large amount of erosion it has suffered compared with the Wisconsin till have been mentioned on a previous page, where it was shown that in many places only the coarser materials of the drift—the pebbles and bowlders—remain as evidence that the ice sheet once covered the region. But the color of the pre-Wisconsin till is generally unlike that of the Wisconsin drift. The latter is commonly light yellow to light gray in color as exposed in railroad cuts or along stream valleys, but where the deeper till appears in fresh excavations it is seen to have the blue color of the unoxidized clay. The pre-Wisconsin till, on the other hand, where best exposed on Sand and Clear creeks in northeastern McKenzie County (Fig. 8), is dark gray in color throughout the maximum observed thickness of over 100 feet.

FIG. 8.—The valley of Clear Creek where it cuts through the moraine of the pre-Wisconsin drift, northeastern McKenzie County.

Except in the morainic areas the thickness of the pre-Wisconsin drift is not great. West of the Missouri River it is seldom as much as 8 or 10 feet and generally the thickness is not over 2 or 3 feet or less. The thinness of the older drift is due partly to erosion which has removed much of the glacial material and over a large part of the area left only bowlders or a thin veneer of gravel, but partly perhaps also to the fact that the drift may never have been very thick in this region.

BOUNDARY OF THE PRE-WISCONSIN DRIFT

Chamberlin and Salisbury many years ago noted the presence of an older drift beyond the Altamont Moraine and its approximate boundary was shown on their map.[1] The more detailed work of

[1] "Terminal Moraine of the Second Glacial Epoch," *Third Ann. Report U.S. Geol. Surv.*, pp. 291–402; also Plate XXXV.

recent years has shifted the margin somewhat farther west and south and it is now provisionally located as shown on the accompanying map (Fig. 9).

Glacial drift is found 50 miles south of the mouth of the Yellowstone River, or within less than 15 miles of Glendive, Montana. For a distance of 50 miles east of the western boundary of North Dakota the drift margin extends approximately east and west and lies 30–40 miles south of the Missouri River. North of the Killdeer Mountains the boundary swings sharply to the south, and crossing the Knife River near the western edge of Dunn County it takes a general southeasterly course across the state. The margin of the drift is believed to cross the Northern Pacific Railroad and the Heart River between 2 and 3 miles west of Gladstone. That a lobe of the ice sheet crossed the Heart River at Gladstone is shown by the presence of thick deposits of drift gravels on the upland 1–2 miles south of the Heart and at an elevation of between 100 and 200 feet above river-level. In places the gravel and sand have a thickness of at least 90 feet, and the deposit contains a number of good-sized granite bowlders. A well-defined gravel ridge marks the edge of the drift for 3 or 4 miles in this area south of the Heart River at Gladstone. This ridge rises 30–40 feet above the surface on either side and falls away rather abruptly on the south, while on the north the slope is more gradual.

There is no evidence that the ice sheet extended more than 2 or 3 miles south of the railroad between Gladstone and Richardton, but in this vicinity glacial gravel and a few small bowlders occur that far south. Between the Cannon Ball and Heart rivers glacial bowlders are found as far west as Elgin, or within 12 miles of the western border of Morton County. In general the drift margin between the Killdeer Mountains and the South Dakota line lies from 40–60 miles west of the Missouri River.

Thickness of the ice sheet.—In the vicinity of Berg in northeastern McKenzie County there are twelve or fifteen high buttes, known as the Blue Buttes, which are irregularly distributed over an area of 15 or more square miles. Many glacial bowlders occur on top of these buttes at an elevation of over 2,700 feet above sea-level, or 1,000 feet above the Missouri River only 6 miles to the east.

Since the buttes rise nearly 500 feet above the surrounding upland the ice sheet probably had at least this thickness in order to override them and deposit bowlders on their summits. Another

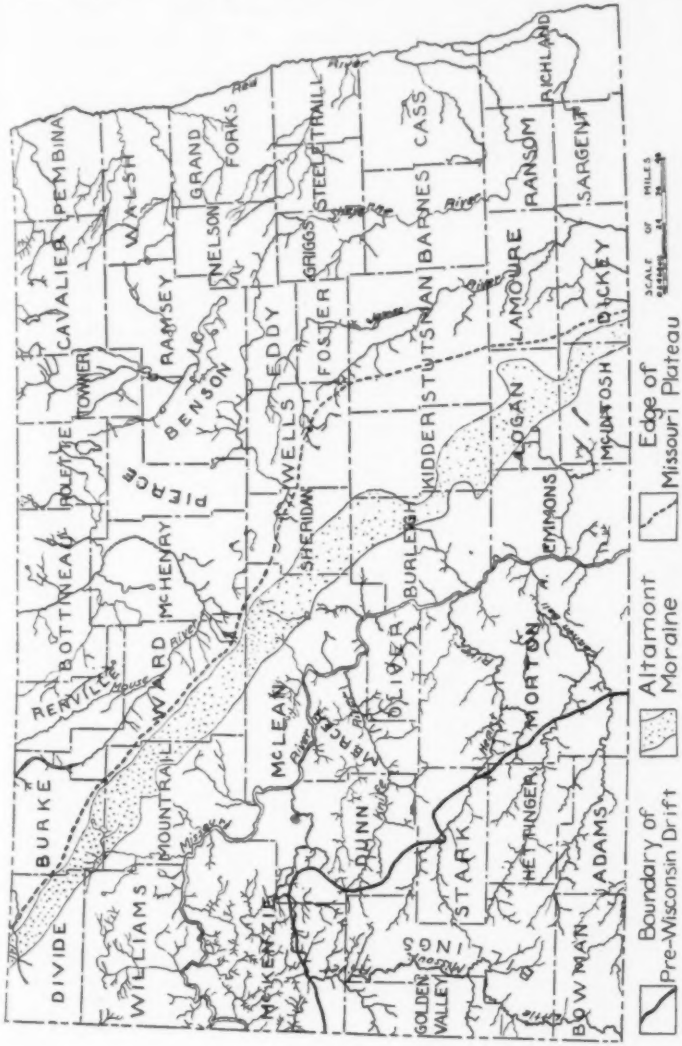

FIG. 9.—Map showing margin of pre-Wisconsin drift and Altamont Moraine in North Dakota

explanation for the presence of the bowlders on top of the high buttes is that the ice upon encountering these obstructions was buckled up as it passed over them. But it seems more probable that the ice sheet which was able to push across the deep valley of the Missouri River and advance 40–60 miles beyond was thick enough to submerge the Blue Buttes and pass on over them. The terminus of the continental glacier was not far from 15 miles south of the Blue Buttes, since the ice advanced only as far as the Killdeer Mountains. Back about 15 miles from the edge the ice sheet therefore doubtless had a thickness over the upland plain of considerably over 500 feet. The ice which filled the Missouri River Valley must have had locally a thickness of 1,000 feet or over.

Age of the older drift.—That the drift west of the Missouri River is much older than the Wisconsin drift is evident from the great amount of erosion it has undergone. Over much of the region the finer materials of the till have been swept away, leaving only bowlders and gravel. The older drift also differs in color, being considerably darker than the Wisconsin. This pre-Wisconsin drift has commonly been regarded as Kansan and there is perhaps more reason for referring it to the invasion of the Kansan ice sheet than any of the other early ice invasions.

The drift north of the Missouri River and west of the Altamont Moraine appears to be younger than the drift south and west of the river. It has undergone less erosion and resembles the typical Wisconsin till in color. Calhoun believes that the drift of northeastern Montana is of Wisconsin age, and on his map this drift is shown as extending to within about 40 miles of the North Dakota line.[1] The extra-morainal drift north of the Missouri River in Williams County is undoubtedly continuous with the drift sheet west of here in Montana, in which case it is probably of Wisconsin age, and belongs to the Early Wisconsin stage.

If this view is correct, there are three drift sheets in North Dakota—the Late Wisconsin east of the Altamont moraine, the Early Wisconsin west of the moraine and north of the Missouri River, and the Kansan drift west and south of the river.

[1] Fred. H. H. Calhoun, "The Montana Lobe of the Keewatin Ice Sheet," *Prof. Paper No. 50, U.S. Geol. Survey*, 1906, pp. 52–57.

EVOLUTION OF THE BASAL PLATES IN MONOCYCLIC CRINOIDEA CAMERATA. II

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PART II

2. CHANGES PRIMARILY MODIFYING THE RELATIONS OF PLATE CONTACT AND POSITION

The second series of changes, those which modify the primary position and relation of the basals and radials, will now be considered. These are: (*a*) reduction and compensating growth; (*b*) enlargement and compensating reduction; (*c*) plate division; (*d*) plate migration; (*e*) plate interpolation; and (*f*) anchylosis.

a) *Reduction and compensating growth.*—Reduction, or the diminution in size of a plate, may be either a function of the absorptive ameboid cells (see p. 502), or due to inhibited growth (atrophy). That is, the absorption of a fully outlined plate may take place, as in the absorption of the anal and oral plates in *Antedon*, or a continuous diminution in development to a former standard of size may result in the atrophy and final disappearance of a plate, as in the great reduction of the basals in *Pisocrinus quinquelobus*[1] and the disappearance of the first costal in some specimens of *Eucalyptocrinus rosaceus*[2] and *Alloprosallocrinus conicus*.[3] Atrophy in plate growth may be due either to plate contact, which inhibits the free branching and anastomosing type of development, or to some deep-seated morphological change. The simplest form of inhibition in plate development is that shown in the normal growth of plates after coming into mutual contact. It is the process which

[1] Ref. 5, p. 27.

[2] Ref. 28, p. 90, Pl. XI, Figs. 6, 7.

[3] In *Alloprosallocrinus conicus* the writer has found that the apparent anchylosis of the costal plates (see ref. 39, p. 407) is due to the complete reduction of the first costal.

gives to the plates their polygonal outline and must not be considered a form of atrophy. Plate contact does, however, produce atrophy when the accelerated growth of one plate causes the reduction in size of some adjacent plate. This type of inhibition may be termed superficial atrophy, and is apparently the type just illustrated in the absorption of the first costal in *Alloprosallocrinus*. Atrophy of the other type is apparently the result of marked internal changes which appear on the exterior in the reduction of skeletal parts. This form of inhibition may be termed deep-seated atrophy, and is the type illustrated in the drawing together of the posterior radials in *Pterotocrinus* upon the reduction of the anal plate (Pl. III, No. 11.)

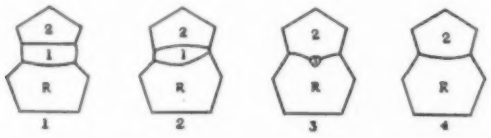

Fig. 6.—Figures showing the reduction of the first costal in *Alloprosallocrinus conicus:* 1 and 2, from specimen No. 9350; 2 and 3, from specimen No. 9357, in the University of Chicago collection.

With the decrease in diameter of a plate in a closed cycle there must be (1) a compensating increase in the diameter of some plate or plates in the same cycle, or (2) a decrease in diameter of some plate or plates of the apposed cycle; otherwise the symmetry of the cup will be distorted. The first principle is clearly demonstrated by the increase in diameter of the first interbrachial plates in *Amphoracrinus*[1] upon the gradual reduction of the proximal portion of the second anal plate. The second principle is clearly demonstrated in the reduction of the apposed compound basal and radial of *Zophocrinus*.[2]

This form of change might be confused with vertical plate-splitting followed by anchylosis of the parts to the adjacent plates if the change were a sudden mutation and no knowledge of the ontogenetic development obtainable; otherwise the phylogenetic succession would show the factors involved. If the reduction of a

[1] Ref. 32, p. 197.

[2] Ref. 6, p. 151.

plate in a closed cycle is asymmetrical, the growth of one of the laterally adjacent plates will be greater than that of the other, and will, on completion of the reduction, occupy the entire area of the missing plate. This process is shown nearing completion in the reduction of the antero-lateral radials in *Catillocrinus*,[1] and the consequent enlargement of the left posterior and anterior radials, and in *Mycocrinus*[2] in the reduction of the left anterior and dextro-lateral radials. In *Pisocrinus* the principle is diagrammatically shown in both basal and radial cycles, where, by the reduction of two basals and three radials, three basals, two radials, and the radianal are greatly enlarged (Fig. 7, Nos. 1–4).

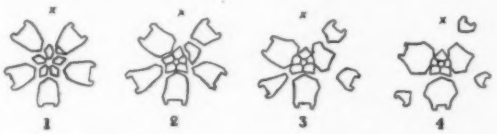

Fig. 7.—Diagrams illustrating reduction and compensating growth in *Pisocrinus:* 1, hypothetical, ancestral stage; 2–4, based upon specimens in the University of Chicago collection; *x* = position of first anal plate.

b) *Enlargement and compensating reduction.*—Plate enlargement, as we have seen, is due to the activity of the ameboid calciferous cells. In normal, symmetrical development the growth of the young plates is for a short time more rapid than that of the body wall, but upon plate contact the increased enlargement of both plates and body wall is theoretically balanced. If, however, a plate increases more rapidly than the adjacent plates, and is not controlled by the inhibiting influence of symmetrical development, and its accelerated growth is not compensated for by growth of the body wall, this growth must be compensated for in some other manner. Accelerated lateral increase of this type in a cycle plate demands then either (1) the decrease in diameter of some adjacent plate or plates in the same cycle or (2) the increase in diameter of some adjacent plate or plates in the apposed cycle and (3) distortion of the horizontal outline of the calyx or various combinations of the first two of these secondary developments may occur.

[1] Ref. 6, p. 149, Fig. LXII.

[2] Ref. 28, p. 110, Pl. 7, Fig. 4.

Accelerated increase of an interpolated plate between cycles or plate groups demands: (1) the decrease in size of some adjacent plate or plates, as in the decrease in size of the dextro-lateral radials in *Pisocrinus* (Fig. 7), upon enlargement of the radianal, or (2) distortion of the cup.

c) *Plate division.*—This process is the splitting of a plate into two (perhaps more) parts, either during or after the formation of the primary, formative cell group. Division of a cell group is due to cell separation, and may or may not be accompanied by cell division. Division of the plates when they are once formed is due to the action of the absorptive, ameboid cells. Division differs essentially from intercalation, in that a fundamentally distinct cell group is demanded for the interpolated plate. But no matter how division may take place, apparent evidences of division in the plates of fossil crinoids must be very carefully investigated before too much significance is attached to the opinion that division and not interpolation has taken place.

Division due to absorption is only known to occur during the absorption of the supporting rods in echinoid larvae,[1] and in the reduction of the radianal in *Antedon*.[2] Division or duplication is assumed by Bather[3] in the formation of the paired, proximal interbrachials in Actinocrinidae, yet all evidence from the work on crinoid larvae shows duplication and not division to be the process involved. Horizontal bisection is assumed by Bather[4] in ten genera of monocyclic Inadunata, not including those in which bisection of the right-posterior radial only occurs. However, when it is noted how closely the development and migration of the radianal in the larvae of modern crinoids parallels the development and migration of the radianal in the Flexibilia,[5] there is good reason to believe that bisection of the right-posterior radial has not occurred, but that the radianal and subradials are primary or interpolated (secondary) plates. Vertical splitting seemed beyond question in

[1] Ref. 34, pp. 349–54.

[2] Ref. 27, pp. 52, 53, Pl. 5, Fig. 11.

[3] Ref. 3, p. 34, fifth notice.

[4] Ref. 6, pp. 112, 144.

[5] Ref. 16, p. 332, 333.

the formation of the compound, left-posterior radial in *Anomalocrinus*,[1] yet Springer[2] has shown it to be an abnormality, *due perhaps to plate fracture*.[3] There are, it is true, certain conditions surrounding apparent cases of plate division which lead us to believe that division and not interpolation has occurred. If, for example, two plates of the same cycle occupy the approximate area of one plate in that cycle, if they mutually fulfil the requirements of but one plate in that cycle, and if in the obliteration of the intervening suture a plate would be formed indistinguishable from the other four undivided plates in that cycle or from the morphologically undivided equivalent of that plate in a closely related ancestral genus, division would seem the only logical conclusion. But this conclusion is by no means proved. In the light of phylogenetic and ontogenetic development as ascertained from fossil crinoids division is very uncertain, for we cannot see the process taking place. Furthermore, if division had occurred anchylosis of the parts to the adjacent plates might take place and either complete absorption with compensating enlargement or migration would have to be called upon to explain the appearance of the new suture. Thus, no matter how carefully we attempt to ascertain the fact that division has occurred, the factor of interpolation will usually appear as an alternative. Only through careful observation, in modern larval development, of plates not destined to obliteration in the adult stage can this process be satisfactorily determined.

d) *Plate migration*.—Any shifting which brings a plate, as a unit, into a new relation of contact and position with plates of the adjacent cycles, or of adjacent plates in the same series, may be termed a migration. For simplification in the discussion, the different types of migration may be broadly separated into two divisions: simple migrations, or those unattended by movements of the sarcode; and complex migrations, or those dependent upon movements of the sarcode. Of the simpler forms, three types occur: portional migration, cell-group migration, and simple plate migration.

[1] Ref. 37, Part III, p. 221; ref. 40, p. 152.

[2] Ref. 32, p. 213.

[3] The italics are the writer's.

If the absorption or atrophy of one side of a plate and the growth on the opposite side are approximately equal, the plate would appear to be shifting as a whole, although actually stationary in part. This type of migration may be called portional migration, and is the type illustrated in the shifting forward of the postero-lateral basals in *Xenocrinus* and sometimes in *Eucalyptocrinus* and *Callicrinus*.

One form of cell-group migration involving the approximation and fusion of two groups into one would occur, if in the previous development of phylitic compression of characters anchylosis were to be carried back into the embryonic period. Thus, anchylosis which appeared as an adult character in early times might appear as an embryonic character in a later stage of development, and cause fusion of the formative cell groups. It is suggested that this type of fusion might be responsible for the interradial development of the two larger infrabasals in *Antedon*.[1] That cell groups as such may migrate in response to physiological stimuli from changed environment without any such evolutional change is also possible, and experimental evidence has been obtained to substantiate this hypothesis.[2]

Simple migration, after plate formation, without tortion or other movement of the sarcode, seems from the very nature of plate growth (see p. 501) to be impossible. This opinion is apparently substantiated by the system of migration of the anal plate in *Antedon*, and of the radianal in *Promachocrinus*[3] and *Hathrometra*,[4] and by the development of the posterior radials in *Antedon* upon the introduction of the anal. Equal spacing of the radials and the anal in the hexagonal stage of *Antedon* is not apparent; on the contrary, the space separating the postero-lateral and antero-lateral radials is much greater than that separating the postero-lateral radials and the anal. As the plates increase by branching and anastomosis, the adjacent margins of the anal and the postero-lateral radials meet and assume a finished appearance (Fig. 10) before the postero-lateral and antero-lateral radials meet. Forward shoving of the postero-lateral radials into this unoccupied

[1] Ref. 8, pp. 288, 289.
[2] Ref. 26, p. 90.
[3] Ref. 16, p. 332.
[4] Ref. 24, pls. 8–12.

area by growth pressure would be expected, but it does not occur. On the contrary, the posterior radials either assume an asymmetrical outline as in *Antedon*, most of the hexagonal Camerata (Pls. II-III), and many of the Fistulata, or the continued widening must be compensated for by accelerated growth of the sarcode in the posterior region. Since no better opportunity for simple plate migration could be conceived, and since it does not in this case occur, there is little reason for believing in its existence.

Complex migrations consist of plate shiftings induced by accelerated growth, tortion of the body wall, in either local or broad areas, which distorts the normal space and contact relation of plates. This form of migration is diagrammatically shown in the carrying up by elongation of the anal tube of the anal in *Antedon*, and of the radianal in *Promacocrinus* and *Hathrometra*. Where the anal and radianal, being more firmly attached to the viscera than to the adjacent plates, are bodily lifted out of the cup into the tegmen by the accelerated growth of the hind-gut, this process is the one which undoubtedly explains the migration of the radianal in all fossil crinoids. A more common form of complex migration, and one shown in many groups of crinoids, is that which results in the formation of biserial from uniserial ossicles in the arms.

e) *Plate interpolation*.—This process, may be defined as the interpolation of some plate or plates, of primary or secondary derivation, between any plates forming the primitive crinoid cup and its appendages. It is one of the most common forms of evolution found in the crinoidea, and may be broadly separated into two groups: primary interpolation, or the development of primary or secondary plates *in situ* from a primary or secondary formative cell group; and secondary interpolation or migration. Only the first type need here be considered, as plate migration has already been discussed. Primary interpolation is the only known method by which additional stem ossicles appear; the new ossicles developing either between the base and the adjacent stem ossicles, as in the Inadunata and Camerata, or between other stem ossicles, as in the Flexibilia. In the development of cirri, primary interpolation is the rule, the interpolation taking place at the proximal end of the appendage. Here too belong the development of the

perisomic[1] interbrachials, of the ambulacrals between the orals and interambulacrals, and of the peculiar plates appearing between the basal and radial cycles of *Acrocrinus*.[2] Interpolation in the basal cycle is known in but two genera. In *Sagenocrinus* and *Homalocrinus* the radianal is incorporated in the basal cycle, and in *Sagenocrinus* especially it assumes the appearance of a basal plate. Interpolation in the basal cycle, being well established in at least two instances, seems very rare, yet this may be due entirely to our lack of knowledge, for the evolution of the radianal plate in the Flexibilia leads one to believe that it appeared in its primitive state in the basal cycle.[3] A discussion of interpolation in the radial cycle has been purposely omitted in the preceding citations, as it belongs more properly in a discussion of the origin of the anal plate, where it will be fully considered.

It appears then that every cycle of plates excepting the infrabasals, and every series excepting the brachials, are affected by interpolation, and even in the brachial series Clark[4] has evidence which points strongly to interpolation. There is then a possibility that every plate cycle and series may be subject to interpolation, but this point is not of immediate consequence and need receive no further attention.

Interpolation in the calyx may demand (1) a reduction in some adjacent plate or plates of the same cycle or group, with or without oblique development of the plates,[5] as in the reduction of the posterior radials and oblique development of the radial cycle in *Antedon* upon interpolation of the anal plate; (2) an increase in diameter of some adjacent plate or plates in an apposed cycle or group, with or without trunkation, depending upon the alternating or superimposed position of the interpolated plate, as in the enlargement and trunkation of the posterior basal in some of the Camerata

[1] Ref. 16, p. 339.

[2] Ref. 39, pp. 805–10, Pl. 53, Figs. 1–3, 4–9, and 10*a*, *b*.

[3] Ref. 31, p. 493, Pl. 5, Fig. 9.

[4] Ref. 13, p. 119.

[5] Oblique development is here used in reference to the displacement of either the proximal or distal ends of a plate, from the vertical axis of the cup and not from the planes of pentamerous symmetry.

and Fistulata upon interpolation of the anal plate, and broadening of the radials without trunkation upon interpolation of interbrachials, as in many of the Camerata; (3) increase in the body wall, as is shown in the lengthening of the calyx of *Acrocrinus* upon interpolation of the extra plates between the basals and radials; (4) interpolation of an extra plate in an adjacent cycle or group to satisfy the demands of plate alternation; (5) deformation of the cup; (6) various combinations of the first four effects named.

f) *Anchylosis.*—The process of anchylosis is provisionally placed under this group of processes, because of its intimate association with certain modifications of plate contact and position which cast some doubt upon the propriety of assuming it to be a result and not the cause of those modifications. This fact is shown in the following section.

ANCHYLOSIS: ITS ANTECEDENTS AND CONSEQUENCES

1. ANCHYLOSIS AND REDUCTION

Anchylosis is the most potent factor operative in the obliteration of sutures, and while it has been discussed as a simple ontogenetic process, its antecedents and results have not been considered. The expression "reduction and anchylosis," so commonly used in the description of brachials, means anchylosis following and depending upon reduction, but whether or not this usage is morphologically correct is not clear to the writer. Anchylosis may take place without reduction, or reduction without anchylosis, although the former is not common. Anchylosis may perhaps be either preceded or followed by reduction, but the writer is inclined to believe that when anchylosis is preceded by reduction the reduction is phylogenetic, and that in ontogenetic development anchylosis is followed by reduction. That is, plates which will appear in the adult as a reduced anchylosed unit are in ontogenetic development up to the time of anchylosis the equivalent of the other plates in the same cycle or series, and with anchylosis inhibition of growth causes the reduction of the compound plate. This inhibition of growth may be due either to deep-seated atrophy in local areas or to local superficial atrophy.

The first change of interest in anchylosis of basals is the change of plate outline, from the pentagons through a heptagon to a hexagon. With lateral anchylosis of two basal plates, the pentagons of the basals are merged into a heptagon, with a re-entrant angle where the supported radial interlocks with the supporting compound plate. Upon further development, absorption decreases the angle of the radial plate, causing it to assume, first a lower angle, then a proximally convex outline, and finally, by complete absorption, a straight angle. At the same time, by increased deposition along the adjacent basal margin, the re-entrant angle of the heptagon is gradually filled, the filling comforming throughout with the reduction of the inserted angle. The final step is the change of the heptagon to a hexagon.

At some time either before, during, or after anchylosis, a remarkably persistent reduction of the compound plate or its component parts occurs. This reduction is parallel to the line of sutural closure, and is sometimes accompanied by reduction in the proximal diameter of the directly supported radial. From the principles set forth in the discussion of reduction and compensating enlargement, either compensating enlargement of the adjacent plates must take place or distortion follow the reduction. When only one pair of basals is anchylosed, as in the *Xenocrinus*, etc., and the *Calyptocrinidae*, the reduction is bilaterally symmetrical; the basals adjacent to the reduced plates are equally enlarged, and the reduction is apparently not due to deep-seated causes and affects only the basal plates and the proximal margin of the apposed radials (Pl. II, Nos. 2, 7). When two pairs of plates are anchylosed, as in the Stephanocrinidae, Pentremitidae, and Platycrinidae, the problem is not so simple, for on one side the compound basals are mutually apposed, and the intervening suture meets the center of the proximal margin of the radial. If the reduction of the compound basals is asymmetrical and occurs only on the sides opposed to the simple basal, no distortion in symmetry is necessitated. If, however, the reduction is symmetrical, there must be a distortion in symmetry of the cup, for there is no basal to enlarge where the compound plates are mutually opposed. In the Platycrinidae the reduction is asymmetrical, and is perhaps due to superficial atrophy.

The simple basal is in general symmetrically enlarged, and the base is occasionally a regular pentagon.

In the Stephanocrinidae and Pentremitidae the reduction of the compound basals is bilaterally symmetrical, and is usually accompanied by reduction of the radials directly supported by the compound plates. This reduction is compensated for on the anterior side by lateral growth of the simple basals and the radials obliquely supported by it. On the posterior side, however, distortion has taken place. If absorption had caused the reduction, either plate shoving or shrinkage of the sarcode would be necessary to keep the plates in contact; but plate shoving is apparently impossible, and shrinkage of the sarcode improbable. Upon comparison of the ornamentation in the reduced and unreduced radials in *Stephanocrinus*, another change seems to have taken place. The neural ridges of the reduced radials are fused, forming a single broad ridge, which apparently indicates that the underlying nerves are in closer relation than in the other radials. The reduction seems, then, to have been caused by the inhibition of lateral expansion in the sarcode in the reduced areas, and not to absorption, and is a very good example of deep-seated atrophy. In the three-basaled, hexagonal Camerata, anchylosis and reduction of the basals are complicated by the appearance of the anal plate, and cannot now be considered.

2. DELAYED ANCHYLOSIS

In many genera, especially of the hexagonal Camerata, anchylosis takes place at such an early period in development that no trace of the immature forms with unanchylosed basals is preserved. The only hope, then, of locating the missing suture is by delayed anchylosis, or characteristics of ornamentation. Ornamentation has, however, received so little study, and the subject is so broad, that the writer cannot at present give it adequate consideration. Examples of delayed anchylosis, however, are not unknown, and a number of cases will be cited in the latter part of this paper. Delayed anchylosis is simply a nascent stage of anchylosis, due to the inhibition of activity in the ameboid calciferous cells. It may appear in the form of internal or external grooves, or in its

completeness as an unchanged suture. In the latter case, it is in the Camerata always accompanied by the inserted angle of the apposed radial. In the pentagonal Camerata the reappearance of a suture or group of sutures would unhesitatingly be described as cases of delayed anchylosis. In the hexagonal forms, however, doubts might arise concerning the reappearance of the anterior suture in the three-basaled genera and of the right-anterior suture in the two-basaled genera, since such reappearance would, according to Wachsmuth and Springer, indicate the presence of six basal plates (pp. 492–93). There might also be some question as to whether these reappearances are due to delayed anchylosis or resorption; but until more light can be thrown upon the problem of sutural reappearance by reabsorption of the intrasutural deposit, these abnormalities may well be ascribed to delayed anchylosis.

3. ANCHYLOSIS AND THE PHYLOGENETIC REAPPEARANCE OF SUTURES

Anchylosis of the basals, as far as we now know, is an ontogenetically repetitive process, confined to plates and not taking place as a result of cell-group fusion. The basal sutures are always present in ontogenetic development, and constitute phylogenetically a plane of weakness in the compound plate. This is apparently not true of the infrabasals, at least in modern forms, as is shown in the interradial development of two of the infrabasals in the embryo of *Antedon*. Atavistic reappearance of sutures, by delayed anchylosis, is a possibility, but the cenogenic or phylogenic reappearance of a suture lost through anchylosis is another question. The skeleton of the Echinoderm is deposited in the midst of living tissue and remains under the full control of the ordinary processes of growth, reabsorption, and modification by living tissue.[1] The partial or total absorption of plates, the shifting of sutures, and the reabsorption and modification of the basals in the formation of the centro-dorsal are sufficient evidence of this statement. It seems possible, then, that under the conditions of physiological disturbance (loss of vitality) common in the paracme of development,[2] failure of anchylosis or reabsorption of the intrasutural deposit might take place, and the sutures reappear as phylogenetic

[1] Ref. 7, p. 350.

[2] *Ibid.*, p. 350.

characters; but we have no evidence of such a reversion, and, until such evidence is brought forward, theories of descent demanding the reappearance of lost sutures should be carefully scrutinized.

DEVELOPMENT OF THE INTESTINE AND THE CONSEQUENT ZONES OF POTENTIAL WIDENING

"In all the Echinoderm classes it is the digestive tube that controls any departure from pentamerous radial symmetry." This statement by Clark[1] may perhaps be too sweeping in extent, especially when we consider the potency of atrophy and compensating hypertrophy (p. 533) in distorting symmetry; but the fact that the digestive tube is one of the most powerful factors in distorting symmetry cannot be too strongly emphasized. The most striking and therefore the most widely known effect of this power is that shown in the various distortions of the mouth and ambulacral grooves by excessive growth of the hind-gut. These tegminal distortions have been so frequently described that there is no necessity of reviewing them here; distortions produced by the intestine in the basal and radial cycles have, however, received too little attention.

In the development of the digestive system in *Antedon* the gastric sack is elongated horizontally into a form somewhat resembling the human stomach, having a large end into which the funnel-shaped oesophagus opens, and a small end with a caecal termination, which is the potential intestine. Upon further development the intestine is also horizontally prolonged, and coils to the right, around the stomach, in the space left for it by the enlargement of the calyx;[2] before the coil is completed, however, the anal appears and the intestine directs itself toward that plate. The pressure exerted by the intestine upon the anal tends to keep separated the posterior radials and prevents the right-posterior radial from encroaching upon the anal.[3] Soon, however, the intestine turns upward and carries the anal with it into the tegmen. The thrust exerted by the outward growth of the intestine which displaces the anal and also the radianal (see p. 538) must not be con-

[1] Ref. 16, p. 152.

[2] Ref. 12, pp. 227–28.

[3] Radianal. See Ref. 16, p. 333.

sidered as a gentle pressure, nor the displacement of these plates as a gentle process, due only to their much closer association with the intestine than with the surrounding plates.[1] The outward push of the intestine is in proportion to the strength of the calyx walls a powerful force, capable of inhibiting plate growth and of greatly distorting the relations of plate contact and position.

In the recent works of Springer and Clark attention has been called repeatedly to the remarkable parallel between the ontogenetic migrations of the radianal in modern crinoids and its phylogenetic migration in fossil forms. Since the migration of the radianal in recent forms is caused directly from its intimate association with the hind-gut in its upward growth, there can be no doubt that such an association existed in the ancient crinoids, and that the tendency for shifting the radianal gradually increased and the association became so firmly established that the radianal is now completely withdrawn from the cup in individual development.

The radianal in the early Flexibilia is incorporated in the basal cycle below the right-posterior radial, and probably appeared in that position in the ancestors of the Flexibilia.[2] The outward push of the developing intestine was then directed obliquely to the right against the radianal and in the succeeding stages shoved and pulled this plate upward and to the right into the posterior interradius and out of the cup. Furthermore, in *Sagenocrinus*[3] it permitted such an enlargement of the radianal that the right margin of the posterior basal was shoved to the center of the posterior interray. This change is of especial interest in the study of basal plate evolution, as it shows one method of obtaining a posteriorly directed basal suture, such as is exhibited in all genera of Camerata having a hexagonal, tripartite base.

This apparent digression from the subject of basal plate evolution in the Camerata—a group in which, as far as we now know, a radianal plate never appeared—is for the purpose of bringing clearly to mind the powerful effect of the growing intestine and the presence of zones of potential weakness in the calyx. These zones of weakness lie along the posterior interradius in the radial cycle

[1] Ref. 11, p. 732.

[2] Ref. 31, p. 439, Pl. V, Fig. 9.

[3] *Ibid.*, Pl. VII, Fig. 18.

and along the right-posterior radius in the basal cycle, and it is to the latter zone that especial attention is called. Wachsmuth and Springer have noted this zone of potentiality in but one instance (description of Fig. I, No. 7, of this paper), although it seems the only zone of potentiality in the basal cycle which can logically be accounted for. Pressure from the end of the developing hind-gut must from the necessity of its position be directed obliquely to the right against the posterior interradius, and any lateral pressure of the gut must be directed against the right side of the calyx, the two combining to shove the right side outward and away from the left side. Thus the stress produced by this shove would naturally fall along the right-posterior basal suture, as this is the nearest suture or plane of expansion adjacent to the posterior interradius within the zone of pressure exerted by the hind-gut.

ORIGIN OF THE ANAL PLATE

Comparison of the cup and tegminal structures in the Batocrinidae and Platycrinidae shows that a very long period of time must have elapsed, or very rapid evolution have taken place, before such a highly specialized form as *Tanaocrinus* could have originated from any of the early Platycrinidae. Since *Tanaocrinus* is an early Silurian (Richmond) genus, relationship can be established with the Platycrinidae only through Ordovician or pre-Ordovician ancestors; therefore, if *Tanaocrinus* is related to the Platycrinidae, it must have been derived from a form having a simple, pentagonal, five-basal cup. The primary step in the evolution of this form into *Tanaocrinus* would be the introduction of the anal plate into the radial cycle, thus giving to the cup its hexagonal outline, and inducing in the basal-plate cycle a remarkable series of modifications. The questions then arise: How do we know that the anal was a secondary and not a primary plate? At what period in the ontogenetic development of the Camerata was it interpolated in the radial cycle? Where did it originate? And what changes followed its interpolation? It is generally agreed that the anal plate in the hexagonal Camerata is of secondary origin. If this is true, the statement just made concerning the ancestry of *Tanaocrinus* is undeniable, for by eliminating the secondary plates of

that genus and restoring the orals an ideal larval or ancestral form will appear. If, however, the anal plate is a primary plate in the radial cycle, a different line of descent is indicated.

In the ontogenetic development of the skeleton in the living *Antedon* the anal plate is interpolated after the basals and orals have formed closed cycles, and before the radials are laterally in contact. As the anal expands by lateral and proximal growth, it comes into contact with the posterior radials and the posterior basal; but this happens before the distal margins of the basals are completed and while the radials are still separated from each other. Since growth in the anal plate and the posterior radials does not cease upon their coming into contact, shoving of the posterior radials in the direction of the unoccupied lateral areas might be expected. This, however, does not occur. On the contrary, the crowding results in a partial inhibition of growth in the apposed margins, and a marked asymmetry results in the outline of the posterior radials, especially in the right-posterior radial. If comparison is now made between *Antedon* in this stage of development and the early Camerata having a hexagonal base, a striking similarity is seen in the development of the basals, radials, and the posterior side of the calyx. The posterior radials in both forms are asymmetrical and narrower than the anterior radials, and the asymmetry is due to the diminution of the posterior side of the plates, the distance between the center of the radial facet and the plate margin being less in the posterior half than in the anterior half. If comparison is then made between the relative position of axial lobes and radial plates in pentagonal and hexagonal Camerata, a further distortion is noted in the hexagonal forms. The lobes of the canal in the pentagonal forms occupy an interradial position, while either two or three of the lobes in the hexagonal forms occupy a radial position. These facts show that there is a distorting factor present in the posterior side of the cup. When it is considered that pentamerous symmetry is the rule in Echinoderms, and that sutural symmetry based upon the hexamerous plan only appears in the basal cycle with the appearance of the posteriorly directed basal suture, there seems to be no other alternative than that the anal plate is the distorting factor, and that it has

developed secondarily in the radial cycle, or has migrated into that position.

The origin of the anal plate is as yet an unsettled question, but there are several possibilities which may well be considered. It may have originated as a secondary plate in either the basal or oral cycle. It may have developed as one of a brachial series, or an interbrachial cycle, or it may have originated as a separate plate in the radial cycle. Origin in the basal or oral cycles is clearly out of the question, for we know of no plates in either cycle from which it could have originated. Assumption of origin as a brachial, which is Bather's explanation for the origin of the anal plate in the Fistulata,[1] is without foundation in the Camerata.

Origin as one of an interbrachial series of the ordinary type is also improbable, for although these interbrachials are present in *Tanaocrinus*, *Xenocrinus*, and *Compsocrinus*, they are clearly formed at a later stage of development. Origin as a first interbrachial, that is, one of an interbrachial series interpolated between the radial plates, has been seriously considered by Carpenter[2] in a comparison of *Xenocrinus*, and some of the dicyclic Camerata, with *Antedon* and *Thaumatocrinus renovatus;* and while such a cycle may have existed and the lateral plates have atrophied, there has been found no record of such a cycle in the monocyclic Camerata. This, however, does not preclude the idea that the anal series may have been so interpolated, and that the lateral plates which appear in some of the dicyclic Camerata have been the result of reduplication.[3] Let us examine the ornamentation in the anal series of *Compsocrinus* and *Xenocrinus*, and see if this may not throw some light upon the question. Bather, in calling attention to the anal ridge in the Reteocrinidae, *Glyptocrinus*, etc., says, "The *anal* ridge is connected with the ridges that unite the posterior basal to the right- and left-posterior radials, and this indicates that an axial cord passed up it to govern the motions of the anal tube."[4] That this ridge does so indicate the presence of an anal nerve seems beyond question, for in comparing the ornamentation in *Xenocrinus* and *Compsocrinus* with the nervous system of

[1] Ref. 4, pp. 319–31.
[2] Ref. 10, pp. 38–46.
[3] Ref. 16, p. 338.
[4] Ref. 6, p. 119.

Thaumatocrinus a striking similarity is discovered. In *Thaumatocrinus* the interradial arms are innervated by secondary branches of the axial cord, which originate slightly above the point of bifurcation of the basal cord, quickly join, and pass up the interradial arms, while the main branches pass up to the radials (Fig. 7, No. 2). In *Xenocrinus* and *Compsocrinus* (Fig. 8, No. 1) the anal nerve ridge arises at the point of bifurcation of the axial trunk ridges in the posterior basal, and there can be little doubt that the branching of the underlying nerves took place in the same manner as they do in *Thaumatocrinus*. The parallel here is so close that the writer was at first inclined to the belief that the interpolation of the anal series in the Camerata is of the same type as the interpolation of the interradial arms in *Thaumatocrinus*. In *Thaumatocrinus*[1] the "interradial" radials appear very early in the ontogenetic development as narrow plates separating the radials and gradually increase to the size of the true radials. An objection to this form of development has been stated by Bather, on the ground that no primitive genera have been found in which the anal plate appears as a narrow linear plate.[2] This objection, however, is not formidable, for the change may have been a discontinuous mutation, or may have taken place during periods of retreat of the sea. Ulrich believes that most mutations have so taken place, for he says in the "Revision of the Paleozoic Systems": " . . . . almost invariably we deal with the nearly finished product of a process of mutation that was begun and established before the new phase invaded areas now accessible to the student of fossil faunas."[3]

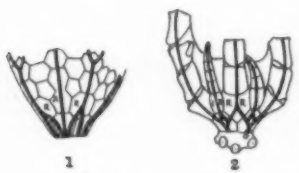

FIG. 8.—Diagram showing the course of the radial and anal ridges in *Compsocrinus* and the branching of the nerves in *Thaumatocrinus:* 1, *Compsocrinus harrisi* (based upon Wachsmuth and Springer); 2, *Thaumatocrinus renovatus* (after Carpenter); course of nerves based upon dissection by the writer.

[1] See Ref. 16, p. 337.

[2] Ref. 3, fifth notice, p. 37.

[3] Ref. 36, pp. 498–501.

The logical sequence of events based upon the *Thaumatocrinus* theory would be the interpolation of the anal plate in the radial cycle and serial development of the succeeding anals. But when this sequence of events is applied to the pentamerous, monocyclic Camerata difficulty is immediately encountered. Either these forms have lost their true anal plate and the anal now appearing in them is the homologue of the second anal in the hexagonal Camerata, or they have developed along a different line of evolution from the hexagonal forms. But before taking up these questions let us examine this theory of interpolation more closely.

Stratigraphically the pentamerous base precedes the hexamerous base, and it seems scarcely possible that a hexagonal form which could give rise to both *Glyptocrinus* and *Tanaocrinus* could have been living in the ocean basin during pre-Ordovician and Ordovician times, and that only those forms having lost the anal plate should have migrated into the epicontinental seas during the Ordovician, while those having the anal plate were withheld until Silurian (Richmond) times. This is apparently carrying the theory of selective action too far to be believed. Again, the embryological evidence shown in *Thaumatocrinus* may not be reliable. We have noted that the radianal in *Promacocrinus* originates to the left of the right-posterior radial; furthermore, we know that the radianal appears in the more primitive crinoids in a subradial position. There has been not only a progressive upward shifting of the radianal in these groups, but there has been apparently a progressively upward shifting of its point of origin. Embryology does not repeat all the ancestral characteristics step by step and then eliminate them in a different fashion in producing the various genera and species; certain characters which are gradually being eliminated phylogenetically are probably, in Crinoidea, the result of a progressively increasing inhibition of plate development in the larva, which ends in the complete obliteration of the plate.[1] Since embryology does not repeat all the ancestral stages, and does in this case permit of changes in the position of origin of a plate, there is a possibility that the "interradial" radials in *Thaumatocrinus* did

[1] For a more complete discussion of this phase of development based upon a wide series of observations, see Ref. 23, Chap. III, "Recapitulation."

not originate in the position in which they now originate, and too much dependence should not be placed upon this character. The evidence presented by fossils is fixed, although often wrongly interpreted, and until stronger evidence is submitted it is well to hold closely to that presented in the stratigraphic succession.

Stratigraphically the pentamerous base preceded the hexamerous base, and when we consider with this the evolution of the two-basaled, hexagonal Camerata, a more logical theory of development for the anal plate is presented. In this short-lived group we have a very rapid evolution from some platycrinid stock. The anal plate in *Platycrinus* originates in the posterior interray between the distal margins of the radial plates, while the anal plate in *Dichocrinus* projects above the level of the radials and costals and bends sharply inward toward the anal tube; its distal portion is reduced, and, if it were separated from the enlarged proximal portion and slightly modified, could not be distinguished from the anal in *Platycrinus*. Enlargement and downward growth of the anal seems then to have occurred, and a different theory is offered for the interpolation of the anal plate.

This theory for the appearance of the anal plate is, then, that the anal plate is of secondary derivation; that it was interpolated phylogenetically after closure of the radial cycle, but ontogenetically after the basal had formed a closed cycle and before the radials had come into contact. The cup in this stage of development is in a flexible condition, and readjustments can readily be made. Development of the anal plate in this position requires no true migration to come into contact with the posterior basal; portional migration, or proximal growth with distal inhibition in the younger stages, will produce the *Tanaocrinus* type of anal, while distal growth alone is necessary to produce the *Glyptocrinus* type of anal. The stimulus which kept the radials apart and permitted this downward growth of the anal plate was the demand for room on the part of an enlarging hind-gut, and it is this stimulus which has caused some of the most remarkable changes in crinoid evolution. Additional plates in the anal series were probably added as needed, for protection of the anal tube, and no slipping downward of a completed series of anals is required. In considering this change

we must remember that we are not dealing with a completed model in which the plates are of fixed and unchangeable size, and in which every change of plate position must be accompanied by an entire readjustment of the adjacent plates; we are dealing with a growing organism in which there is a certain amount of flexibility in adjustment by plate growth.

If this theory for the interpolation of the anal plate is correct, the first anal plates of *Glyptocrinus*, *Platycrinus*, and *Dichocrinus* are homologous; and in further developing the theory for the evolution of basal plates this view will be followed.

[*To be concluded*]

DIFFERENTIATION IN INTERCRUSTAL MAGMA BASINS

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Dr. N. L. Bowen's comprehensive article on "The Later Stages of the Evolution of the Igneous Rocks," issued as a supplement to the last volume of this *Journal*, will be hailed with satisfaction by all petrologists, and indeed with gratitude by those who have the misfortune not to be chemists. It contains the first serious attempt to deal with the problem of magmatic differentiation directly from the standpoint of experimental knowledge. In demonstrating how the course of crystallization may be changed by the sinking of crystals, or the straining away of liquid from crystals, or the formation of zoned crystals in isomorphous groups of minerals, the author scarcely goes beyond actual laboratory experience, and his conclusions accordingly carry a great weight of authority. When he proceeds to construct on this basis a general theory of differentiation, the element of hypothesis is necessarily introduced, and, as the author recognizes, his argument can no longer command unquestioning acceptance. It is a very interesting contribution to a discussion which is not likely soon to be closed.

I wish to make a few remarks upon one of the subsidiary issues, which, however, touches the main theory at numerous points, viz., Bowen's predilection for differentiation *in situ* as opposed to differentiation prior to intrusion. That an appreciable settling down of crystals may take place after intrusion is not to be denied, but I think that the experience of any field geologist goes to show that it is a rare and exceptional incident. Daly has given a list of about thirty stratified sills and laccolites in which such "gravitative" differentiation is believed or conjectured to have occurred, but probably a critical examination would dispose of many of the examples cited. In some, such as the Loch Bordan mass in Sutherland, there is not a gradual transition but a sharp boundary between the several

rock types. Bowen remarks that the upper acid magma, remaining fluid after the lower basic portion has wholly crystallized, may come to have an intrusive relation to the latter. This would be sufficient to explain veining of the one rock by the other; but, where an overlying sheet is separated from an underlying one by a surface of discontinuity, I can see no explanation but that of distinct intrusions. Nor is this explanation necessarily excluded even when no sharp division is seen, for, under appropriate conditions, a transitional zone may result from partial admixture. The Sudbury laccolite is probably a case in point, though I must confess to only a limited personal examination of the mass. I found no indication of a regular "composition gradient" in either norite or granophyre, considered separately, while the transitional zone between them has all the characters of a hybrid rock. The sulphide ore I leave out of count, as doubtless representing a magma immiscible with that of the norite. The clear instances of gravitative differentiation in sills and laccolites of which I have direct knowledge are all in rocks which must represent very unusually fluid magmas, such as the analcime-bearing intrusions of Permian age in Scotland. They are the kind of exceptions which help to prove the rule: viz., that in an intrusive body of moderate size a prohibitive viscosity soon puts a stop to the settling down of crystals. Doubtless a laccolitic mass of very large dimensions retains its fluidity longer, but it is obviously in a great intercrustal reservoir that the most favorable conditions for this action will be realized.

Bowen would apply the conception of differentiation in place to the plutonic rocks of Skye; but the facts, as I see them, absolutely negative such a hypothesis. The peridotite is not found at the base of the gabbro, but enveloped in the midst of it. The granite breaks through the gabbro, and, where any approach to a stratiform arrangement is apparent, does not overlie, but underlies, the basic rock. In one part the granite has been so chilled against the gabbro that its margin and the offshoots from it assume the characters of a spherulitic rhyolite. I infer that the gabbro was, in this place, not only solid but cold when the granite was intruded. The large gabbro laccolite itself is made up of numerous irregular sheets, showing differences in composition and structure, and often

visibly cutting one another. In the peridotite this composite structure is more strikingly exhibited, and it can be detected in places in the granite, which is a much more uniform rock. The several component sheets are not disposed in an orderly fashion in accordance with their various densities. Add to this evidence the fact that peridotite, gabbro, and granite all make smaller separate intrusions, some much too far away from the main complex to have any direct connection with it, and it will appear beyond dispute that the differentiation which yielded these various rocks was effected prior to their intrusion, and therefore in some large reservoir at a deeper level.

Bowen does not refuse the conception of a deep-seated magma basin stratified according to density; but he seems to think it an absurdity that, on that hypothesis, the earlier intruded magmas should be drawn from the lower levels (p. 73). I will try to remove his objections. I have already urged[1] that in order that such a basin may have a considerable degree of permanence, as it obviously has, we must suppose some approach to thermal equilibrium between it and the surrounding crust. This implies a temperature gradient within the basin approximately like the normal gradient in the earth's crust of the region. It implies, further, what I may call a fusibility gradient corresponding with this normal temperature gradient. Now, the separation and sinking of crystals, as pictured by Bowen, goes with a cooling-down of the magma, which terminates in complete solidification. Any intrusions drawn from the basin must therefore be consequent upon *remelting*. The occasion of this I presume to be a gradual rise of the isothermal surfaces, which must accordingly become more closely spaced. In other words, reheating implies a temperature gradient steeper than that to which the fusibility gradient is adjusted, and it follows that the lowest layers will first become fluid. I have not attempted to develop this view of the matter, and should welcome criticism; but Bowen's zeal for differentiation in place has caused him to pay little regard to the possibilities of this alternative.

I am wholly in accord with Bowen in the conviction that alkaline and calcic rocks are derived from the same primitive magmas

[1] See especially *Compte Rendu XII Congr. Géol. Intern.*, Toronto, 1914, pp. 205–8.

(p. 59). My belief has been, and is, that the differentiation of these two great classes of magmas from the common stock and the separation of them—in general in a horizontal sense—constitute the first and most important steps in the evolution of igneous rocks. Why the chemical differentiation should so consistently follow these lines has been a difficult problem, and it is the more gratifying to be offered at least a partial answer to the question. Stated broadly, Bowen's ideal scheme of differentiation leads first to a series of calcic rock types and subsequently, if continued, to an alkaline series. There are qualifications of this rough statement which I do not go into here; but in general it appears that, if a separation can be brought about at a certain well-defined stage of the progressive differentiation, it will be a separation between calcic and alkaline. This separation, I hold, has actually been effected on a grand scale, and I have sought the immediate cause of it in the action of crustal stresses squeezing out the residual fluid.

A discussion of this suggestion from the chemical point of view would be instructive, but here Bowen disappoints expectation. He dwells on particular cases in which separation has not taken place at the stage specified, but at a somewhat earlier stage; and he throws doubt upon the existence of any general regional distribution of alkaline and calcic rocks, such as Iddings demonstrated long ago. The fact that, among the younger rocks of North America, alkaline types characterize the Atlantic slope and calcic the Pacific, he would explain by supposing that erosion has exposed deeper levels on the western side of the Rocky Mountains than on the eastern. He forgets that the contrast of petrographical facies holds good for the lavas as well as for the intrusive rocks. Moreover, the fact that lava flows still cover vast areas on the western side, while on the eastern they have mostly been removed, makes it difficult to accept his statement about the relative amounts of erosion.

As regards the association of calcic rocks with regions subjected to powerful lateral thrust, nothing would be gained by traversing old ground again, but to Bowen or any other unbeliever I will offer just one consideration. If we examine those crystalline schists which are admittedly of igneous origin, together with foliated

igneous gneisses, we find that they belong almost exclusively to the calcic branch. A few exceptions there are, and must be. A nepheline syenite may be intruded in a line of faulting during the time of movement, as in the Langesundsfjord; or it may be crushed and metamorphosed long afterward by stresses with which it has no genetic connection, as at Loch Borolan; but these are isolated and incidental occurrences. The matter is easily brought to the test. In Grubenmann's classification, based solely on chemical composition, the crystalline schists and gneisses of igneous origin are contained in six of the twelve groups. The calcic rocks are in Groups I, III, IV, and V, which correspond with granites, diorites, gabbros, and peridotites. They include a rich variety of types, and collectively make up enormous tracts of the earth's crust. To complete his classificatory scheme the author has been able to produce various types of alkaline rocks, which scantily furnish forth Groups VI and VII, but most of them are little more than petrographical curiosities. In respect of the total bulk of all known occurrences, these alkaline crystalline schists as a whole are quite insignificant as compared with any single type in the calcic division.

The striking disparity here noted is only one consideration among others which points to a peculiar distribution of alkaline and calcic igneous rocks in relation to crustal stresses. If anyone seriously believes that such things are matters of chance coincidence, there is no more to be said. It is to be hoped rather that chemists, as well as geologists, will recognize here a real significance, and will lend their help in the attempt to explain the facts, not to explain them away.

STRATIGRAPHY OF THE SKYKOMISH BASIN, WASHINGTON

WARREN S. SMITH
Berlin, Washington

WITH

REPORT UPON PALEONTOLOGY AND PALEOPHYTOLOGY

CAROLINE A. DUROR

STRATIGRAPHY

I. GENERAL AREAL DISTRIBUTION

In general, the rocks of the Skykomish Basin trend in a north-south direction. This is almost exactly true of the igneous and metamorphic terranes. Only the sedimentary Swauk and the tufaceous Keechelus series vary from this general statement, for they show a trend in general west of north but bending northward on their northern prolongation. Dawson has remarked this tendency of all the rocks of the Cordilleran system.[1] The rocks lie in roughly parallel bands in the north, but are replaced southward until the granodiorite entirely takes the place of the earlier series and extends over nearly the entire width of the quadrangle. Igneous rocks greatly predominate in the area, metamorphics and sedimentaries being approximately equal in amount, and both being comparatively small. Volcanics make up a smaller division. These relations will be illustrated by the following classification table:

Snoqualmie granodiorite	130.90
Keechelus andesitic series	32.20
Tye soda granite and Beckler stock	24.15
Easton schist	22.95
Swauk sedimentary series	56.00
Maloney metamorphic series	14.80
Index granodiorite	4.35
Surface outcrop areas	285.35 sq. mi.

[1] G. M. Dawson, "Geological Record of the Rocky Mountain Region in Canada," *Bu Geol. Soc. Am.*, XII (1901), 59.

In the following discussions no effort will be made to subdivide the metamorphic rocks of a sedimentary origin from those of an igneous origin, where these are so intimately associated as to make the subdivision impracticable. However, the schists of the northeastern area are easily kept distinct from the metamorphic series of the northwestern area.

On stratigraphical grounds the rocks readily fall into two groups: (1) the pre-Tertiary, and (2) the Tertiary. The division line between these is the most marked unconformity in the Cascades. We have present a schist, belonging to the pre-Tertiary, which is cut by quartz and igneous rock dikes, making the oldest or basal terrane.

This is called the Easton schist, and it forms the metamorphic terrane in the northeast. No definite idea of its age can be suggested except that it is pre-Ordovician. Fragments of it are included in the Mesozoic batholiths, and it is more complexly folded than the Maloney (Gunn Peak) metamorphic series. The next younger series belongs on paleontologic and correlation evidence to the Ordovician. It is a series of quartzites, schists, and crystalline limestones with associated greenstones, approximately 4,000 feet thick, outcropping in the northwest. Weaver correlates this series with the Cache Creek series as defined by Dawson.[1] It has at least one stage less of dynamic history than the Easton and on lithologic grounds it is believed to be equivalent to Smith's Peshastin series of the Snoqualmie area; but its fossil content identifies it as Ordovician instead of Carboniferous, as the Peshastin is called by Smith and the Gunn Peak by Weaver. Nothing can be said of the remainder of the Paleozoic history of the area. The absence of later Paleozoic and Triassic seems to be general in the region of the Cascade Mountains. In Jurassic time, however, there was a notable period of deep-seated volcanic activity, resulting in the intrusion of the great Sierra Nevada-Cascade granodiorite batholith, possibly the greatest of igneous intrusions.[2] This batholith is represented by two terranes in the Skykomish Basin. The first is the Tye soda granite in the northeast, and the second

[1] G. M. Dawson, *Ann. Rept. Can. Geol. Surv.*, N.S., VII (1894), 37B–49B.

[2] R. A. Daly, *Igneous Rocks and Their Origin* (1914), p. 53.

is the Index granodiorite in the northwest. The Cretaceous is not represented but is known to occur as a marine series farther northward. Following the Mesozoic batholithic intrusion came a positive orogenic movement, corresponding to the Laramie revolution, which left the Cascade area, at the close of the Mesozoic, high above sea-level.

The Tertiary period opened with a period of continental deposition in which the Swauk sandstone was deposited unconformably on the eroded edges of earlier metamorphic rocks. These arkoses consist of mingled fragments of granitic rock and of schist derived from the Paleozoic metamorphic series and from the Mesozoic batholith. Both Smith and Willis consider these arkoses to be lake deposits, but Weaver more correctly designates them as purely continental. They show conglomeratic facies and cross-bedding and vary so markedly in thickness that only the maximum figure of 4,000 feet is of any significance. They are equivalent to the lower Puget of western Washington and, on paleophytological grounds, to the Fort Union of the Montana-Wyoming areas. No definite information is recorded of the late Eocene and Oligocene, the gap being succeeded by Miocene andesitic tuff beds. These are volcanic tuff ejectamenta cut by dike- and sheet-like intrusions of andesitic composition. We have insufficient evidence to suggest where these tuffs had their immediate source, but their chemical resemblance to the Miocene granodiorite suggests forcibly that they were derived from the same magma. In later Miocene a recurrence of deep-seated vulcanism took place, resulting in the injection of the Snoqualmie granodiorite, which is the most important terrane present in the area. This batholith, if its texture is to be accounted for, must have been covered by at least 2,000 feet of rock. In this cover late Eocene and Oligocene may be included. In latest Miocene and in early Pliocene the region was planed to a low relief; a disturbance of isostatic equilibrium followed, which resulted in the arching up of the Cascade Mountains to a maximum height of approximately 8,000 feet. Since this Pliocene uplift, canyons some 5,000 feet deep have been cut in the granodiorite, a fact bearing witness to the severity of erosion experienced by the area.

In the Pleistocene the Skykomish Basin was eroded by valley glaciers, and the only discernible post-Tertiary volcanic history is recorded in a thin layer of ash, probably drifted from Mt. Rainier by prevailing southwest winds. Post-Pleistocene time has not lasted long enough seriously to change the aspect of the topography left by glaciation.

II. PRE-TERTIARY HISTORY

PRE-MESOZOIC

The pre-Mesozoic is represented by two divisions, one of which is considerably older than the other, and on lithologic grounds is referred to an equivalency with the Easton schist. The later division has experienced at least one stage less of metamorphic history and is of known Ordovician age, on the evidence of fossils obtained from a cherty phase of the limestone lens outcropping in Lowe Gulch (D 2), two miles west of Grotto. No evidence of the exact age of the Easton schist has been put forth and none can be suggested for the Skykomish Basin. It comprises extremely metamorphosed and crumpled rocks generally derived from sediments. This structural condition of the rocks precludes any estimate as to their original thickness, but does enable one to infer that they are of considerably greater age than any other Paleozoic division which is much less dynamically disturbed.

MALONEY

The Maloney comprises a series of metamorphosed rocks including quartzites, limestones, and schists of sedimentary origin cut by basic igneous rocks, usually best described as greenstones, which are later in age than the Maloney, but which on the evidence of their extreme metamorphism are considered to be also of Paleozoic age. The name Maloney is applied to a series formerly believed to be equivalent to the Peshastin series, which is called Carboniferous in age. The evidence on which this correlation is made is presented in an earlier paper.[1] Subsequent identification of fossils found in the limestone lenses shows the formation to be Ordovician in age, and therefore the name Maloney is suggested.

[1] Warren S. Smith, "Petrology and Economic Geology of the Skykomish Basin, Washington," *School of Mines Quarterly*, XXXVI (1915), 157.

Miss Caroline A. Duror, in another part of this paper, has identified the following fossils as of Ordovician age: *Rafinesquina deltoidea* and *Illaenus americanus*. This is the first recorded evidence of the presence of Ordovician strata in the Cascade Mountains of Washington, and both fossils are the first of their kind of Paleozoic age to be found there. With this Ordovician series begins the definitely known geologic history of the Skykomish Basin. It was a period during which the area stood approximately at sea-level, as evidenced by the fact that the limestone lenses carry marine fossils. The presence of quartzite shows that probably the area was not deeply submerged, but more probably was near the continental margin. There is no record of the post-Ordovician Paleozoic.

MESOZOIC

There are no Mesozoic deposits at present, though there is evidence that they must have existed. The sole known event of the Mesozoic in the Skykomish Basin is the intrusion of batholithic igneous rocks whose structural relations identify them as Mesozoic, though there is no other positive evidence of their age. But it is altogether probable that the batholiths were intruded as a part of the great Sierra Nevada intrusion identified in California and Oregon as of Jurassic age. Daly, Smith and Calkins, Russell, Weaver, and others assert this probability. The granodiorite of which this batholith is composed is granitoid in texture, and such a texture can be established only under a thick cover of superjacent rock. This cover was removed in post-Jurassic time, leaving the batholith uncovered at the end of the Mesozoic. Russell[1] and Smith[2] have described sedimentary rocks of Cretaceous age, from Whatcom County to the north, and it is therefore inferred that removal of the 2,000 feet or more of the cover of the Jurassic batholith was toward the north. The series, as described by Smith, under the name Pasayten, begins with a conglomerate in which

[1] I. C. Russell, "Cascade Mountains in Washington," *20th Ann. Rept. U.S.G.S.*, Part II (1898), p. 114; G. M. Dawson, "Geological Record of the Rocky Mountains in Canada," *Bull. Geol. Soc. Am.*, XII (1901), 84.

[2] Smith and Calkins, "Cascade Mountains in Washington," *20th Ann. Rept. U.S.G.S.*, Part II (1898), p. 114.

granitic bowlders predominate, is 6,000 feet or more thick, and is dynamically disturbed. The Mesozoic closed with a period of severe orogenic disturbance, as evidenced by the structural relations

FIG. 1.—Swauk arkose series. Conglomeratic facies

of Tertiary rocks. This unconformity is very marked, because the earliest Tertiary sedimentaries lie at distinct angular unconformity on the pre-Tertiary rocks, a break which is well described by Smith and Calkins in the Snoqualmie area.[1] The pre-Tertiary

[1] G. O. Smith and F. C. Calkins, *Folio U.S.G.S.*, 1906, 2.

disturbance left the area adjacent to the Skykomish Basin on the east in a condition sufficiently elevated to make the earliest Tertiary a period of erosion.

III. TERTIARY

EOCENE

In the Skykomish area the Eocene was a period of sedimentation during which 4,000 feet of arkoses, shales, and conglomerates were deposited. About the middle of the series there are two shale formations which yield a considerable flora. The series is directly continuous with the Swauk series of the Snoqualmie quadrangle, and is also related to it on paleontologic grounds. It outcrops in a belt several miles in width, striking approximately N. 45° W. in the Eagle Creek-Beckler and the Foss River valleys. The dips vary; in the measured section, half a mile south of the Great Northern Railway, the base of the series lies nearly level, with increasing dip to the east as one goes east, and to the west as one goes west, until the top of the series stands vertical. It is an anticline whose basal beds rest unconformably on Easton schist, and whose roof is a part of the Keechelus andesite series.

Miss Duror's appended report is made on the flora collected from two horizons about 600 feet apart vertically, the lower being 1,100 feet from the base of the Swauk. Fossils numbered F 831, F 831+50, and F 844 are from the upper beds; those numbered F 865 from the lower. With the latter is associated a coal bed some 14 inches thick on which slopes have been driven in the hope of finding minable coal.

The sandstones and conglomerates are cross-bedded and the fragments usually angular and never assorted (Fig. 1). It has been considered a fresh-water lake deposit. In the light of the recent developments of stratigraphy it may better be classed as in part purely continental and in part deposited by streams, probably in deltas. The shales, and particularly those carrying complete specimens of *Sabal*, could only have been laid down *in situ* and must have been formed in shallow water—probably in a swamp. None of the series bears evidence of deposition in deep water, and both the angular condition and the considerable size of the fragments forbid their having been transported for any great distance.

Correlation.—Knowlton has done the paleontologic work on the continental Eocene of Washington. He has made the determinations both for the Eocene (Puget) of western Washington and for the Eocene (Swauk, Teanaway, and Roslyn) of eastern Washington. Continual reference is therefore made to him as an authority. The original report on the Swauk[1] showed 25 species belonging to the following genera: *Lygodium*, *Sabal*, *Myrica*, *Comptonia*, *Populus*, *Quercus*, *Ficus*, *Cinnamomum*, *Prunus*, *Diospyros*, *Zizyphus*, *Celastrinites*, *Phyllites*. Of these genera, *Sabal*, *Populus*, and *Ficus* are reported by Miss Duror from the Skykomish Basin, and both *Sabal* and *Ficus* are index fossils of the lower Eocene (Puget), as stated by Knowlton: "The following genera have been found in the lower beds but not at all in the upper: *Cladophlebis*, *Lastrea*, *Siphonites*, *Ficus*, *Eucalyptus*, and *Aralia*."[2] Turning to the western area we find that the Puget formation consists of some 10,000 feet of arkoses and intercalated carboniferous shales representing the Eocene. Besides the above named, Knowlton describes *Quercus*, *Juglans*, *Rhamus*, *Populus*, and *Laurus* from that series. Of these Miss Duror reports *Juglans*, *Populus*, and *Laurus*, and the presence of *Ficus* and *Sabal* correlates the Swauk with the lower Puget (Carbonado). Miss Duror's report further proves the equivalency in age of the Swauk with the Fort Union of Montana, North Dakota, and Wyoming.[3] The Swauk sedimentary series may then be correlated with the lower Puget of western Washington, with the Swauk (lowermost Eocene) of eastern Washinton, and with the Fort Union areas farther east.

MIOCENE

Keechelus.—This series of rocks of volcanic origin comprises tuffs, sheets, and dikes usually of andesitic but less frequently of dacitic composition. The tuffs predominate strongly and form beds of unknown but considerable thickness widely distributed in the Skykomish Basin. They overlie the Swauk sandstone, and the

[1] *Folio 106, U.S.G.S.*, 1904, p. 5.

[2] *Folio 54, U.S.G.S.*, 1899, p. 3.

[3] A. G. Leonard, "Cretaceous and Tertiary Formations," *Jour. Geol.*, XIX (1911), 541–43.

dikes have baked the sandstones. The Keechelus is therefore post-Swauk in age. Contrariwise, the Keechelus series has been indurated and otherwise metamorphosed by the Snoqualmie batholith to the southward; in the Snoqualmie area the Keechelus series is underlaid by a sedimentary series of sandstones and water-laid pyroclastics (Ellensburg) which contains flora called Upper Miocene by Knowlton.[1] The Keechelus series in the Skykomish Basin, being really continuous and lithologically identical with the series of the southern area, is therefore considered Miocene in age. As has been pointed out by Smith and Calkins, a striking chemical similarity exists between the Keechelus andesite and the subjacent body of granodiorite. Both fall into the same chemical classification—tonalose. It is immediately inferred that the two rocks are consanguineous, or, in other words, that the andesitic pyroclastics were blown out from a magma that later solidified as the Snoqualmie granodiorite. We must assume 2,000 feet or more of cover, and it is suggested that this Keechelus series may very well have provided at least a part of the cover which has later been removed by processes of erosion. No estimate can be made of the thickness of the Keechelus series. It is undoubtedly widely variable and probably had a thickness of several thousand feet.

Snoqualmie granodiorite.—Into the Keechelus series was intruded one of the younger of the known great batholithic intrusions. It has a known length of major axis of about thirty miles and is approximately two-thirds as broad. Throughout, this terrane is a massive, fresh, granitoid igneous rock which has been discovered by erosion to a vertical depth of 5,000 feet or more. It has, as was seen above, metamorphosed rocks of late Miocene age, and has sent apophyses into them, and therefore must itself be Miocene or later in age. To account for its holocrystalline nature and for the fact that it has been peneplaned, uplifted, and maturely dissected, it seems necessary to put the date of its intrusion as near that of the Keechelus as possible. The age is therefore given as late

[1] G. O. Smith and W. C. Mendenhall, "Tertiary Granite in Northern Cascades," *Bull. Geol. Soc. Am.*, XI (1900), 224; G. O. Smith and F. C. Calkins, *Folio 139, U. S. G.S.*, 1906, p. 8.

Miocene, in accordance with Smith's interpretation.[1] The only metamorphic effects experienced by this rock are the slight clouding of feldspars and the formation of a system of joints. There is a southernmost corner of another batholith, or, more likely, of a subjacently connected continuation of the same batholith, north of Grotto, and it is probable that these Tertiary batholiths form the core of the Cascade Range throughout the northern half of the state. Daly has correlated several of his batholiths with the Snoqualmie batholith.

PLIOCENE

There is no stratigraphic evidence of Pliocene history. It is physiographic rather. We infer that the Snoqualmie batholith had a cover in excess of 2,000 feet in thickness. This cover was removed and the entire area reduced to one of low relief in late Miocene and post-Miocene time. In the Pliocene the area was uplifted with a broad arch of north-south trend and with certain minor warpings of transverse trend. Subsequent to this uplift, but still in the Pliocene, the area was maturely dissected by steam action. This process of peneplanation, uplift, and mature dissection is evidence of the very considerable duration of the Pliocene.

PLEISTOCENE

This is the age of glacial occupancy, when glaciers of the alpine type filled the valleys to a depth of several thousand feet and flowed down to their confluence with the Piedmont glacier of Puget Sound. Evidence has been put forward by many writers of two periods of glacial advance in the Puget Sound Basin, but of course the last alpine glacier to occupy the valley would have destroyed all evidence of any previous glaciation, and it can only be said that the Skykomish Basin was maturely dissected by glaciers of the alpine type in Pleistocene time. Comparatively little time has elapsed since the glaciers withdrew from the valley. The only stratigraphic evidence of this period is the accumulation to a depth of several inches of a volcanic ash which has only a

[1] G. O. Smith and W. C. Mendenhall, "Tertiary Granite in the Northern Cascades," *Bull. Geol. Soc. Am.*, II (1900), 201–28.

slight soil covering at present—an evidence of recent volcanic activity in the near-by volcanic cones.

RÉSUMÉ

Eocene time witnessed the accumulation of 4,000 feet of arkose sandstone. This was orogenically disturbed so that it now dips at considerable angles. In the Miocene a series of volcanic tuffs and andesitic intrusives were derived from a magma which approached the surface and cooled as a batholith in late Miocene. Pliocene saw the formation, uplift, and mature dissection of a peneplane. The Pleistocene was a period of glaciation lasting nearly to the present, in which the Skykomish area was maturely dissected by ice erosion.

IV. STRUCTURE

A glance at the map shows the tendency of all formations to trend north-south. Only the Swauk arkose series deviates from this tendency, and even this formation tends to assume a normal relation in its northward outcrop. The great igneous terrane (Miocene batholith) has its major axial trend in a direction parallel to the north-south axial trend of the Cascade Range.

JOINTING

There are two known systems of joints of considerable importance and one or more of less prominence. The first two strike N. 45° E. and N. 70° E., respectively, and the lesser system strikes N. 80° W. It is suggested that these joints are the result of pressure exerted by orogenic forces in raising the Cascade peneplane to its present position. If this pressure were exerted continuously in an east-west line from the Pacific side, we should anticipate a set of joints striking N. 45° E. and a lesser set striking N. 45° W.[1] At least one important set of joints does strike N. 45° W. in the Cleopatra Mine. But it is necessary to postulate a change in the direction of application of the force to account for the system of joints striking N. 70° E. and N. 80° W.[2] It seems possible that such a change may have taken place in the direction of application

[1] A. Daubrée, *Géologie expérimentale* (1879), pp. 316 f.

[2] G. F. Becker, "Finite Strain in Rocks," *Bull. Geol. Soc. Am.*, IV (1893), 23.

of orogenic pressure, and this change may account for the transverse warping of the surface of the peneplane which is noted elsewhere. The importance of the development of these structural relations has an important influence on ore deposition (Fig. 2).

FIG. 2.—Kimball Creek. Note jointing. Rock: granodiorite

REPORT ON THE FLORA OF THE SWAUK SERIES

The flora of the beds is of Fort Union age. The material examined yields fifteen genera and nineteen species, of which two are new; the other seventeen species have been recorded from

Fort Union beds. Three ferns are represented by abundant specimens of *Asplenium* and *Pteris* in the shales of F 831 and F 831+50.

GENUS *Asplenium*

Asplenium magnum var. *intermedium* var. *novum* (Duror) (Fig. 3)

Knowlton: "Fossil Flora of Yellowstone Park," extract, *Mono. XXXIII, U.S.G.S.*, 1899, Part 2, p. 667; Pl. LXXIX, Figs. 8, 8*a*.

Heer: *Flora Foss. Arct.*, Vol. IV, "Ostsibriens," Taf. XX (*A. whitbiense*).

This form is so named because it is intermediate in character between *A. magnum* (Knowlton) and *A. whitbiense* (Heer). The frond is not pinnate, but the lobes are cleft one-half to one-third of the distance to the rachis. The margin of the lobes is entire. These lobes are one and one-half to twice as long (along midvein) as broad and come to a rounded point. Secondary veins come off at an angle of about 45°, members of each pair being almost opposite. Each secondary bears eight to ten pairs of tertiaries, which are generally once forked. A few rare cases of simple secondaries and still fewer twice-forked secondaries were observed. The variety differs from *A. magnum* of Knowlton in possessing almost deltoid instead of ovate lobes and in being rather larger. This form is separated from *A. whitbiense* of Heer, because here most secondaries fork once only, and because Heer's form has true pinnules—the form being bipinnate. There is no suggestion that this form is fully even once pinnate.

FIG. 3.—*Asplenium magnum* var. *intermedium* var. *novum*. (½ natural size.)

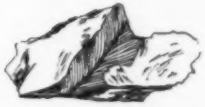

FIG. 4.—*Pteris pennaeformis*. (½ natural size.)

GENUS *Pteris*

Pteris pennaeformis (Heer) (Fig. 4)

O. Heer: *Fl. Tert. Helvetiae* (1855), p. 38; Taf. XII, Fig. 1*a–d;* Miocene age.

Lesquereux: *Tert. Flora* (1878), p. 52; Pl. IV, Figs. 3, 4, *Pseudopennaeformis*, Lower Lignitic age.

The Cascade specimens are quite similar to that figured by Heer, except that here only that part of the pinnae with entire

margins is seen. Secondary veins are seen to fork twice, as in Heer's Fig. 1*e*, though from his description he found such nervation rare.

GENUS *Sabal*

Sabal powelli (Newb.)

Newberry: *Proc. U.S. Nat. Mus.*, V (March 21, 1883), 504.
Later Extinct Floras of North America, p. 30; Pl. LXIII, Fig. 6; Pl. LXIV, Figs. 1–19; Tertiary (Green River group) age of Wyoming.

Palms are represented in these beds, chiefly in F 831+50 and in F 865, by numerous perfectly preserved specimens of this type. In some cases both upper and lower surfaces of the petiole of one leaf were preserved. The forms agree in all respects with Newberry's type.

GYMNOSPERMAE

Gymnospermae are represented by countless fragments of *Glyptostrobus*, *Sequoia*, and *Taxodium*—this last in greatest abundance. The greatest number of these forms is found in the shales of F 831+50.

FIG. 5.—A, *Sequoia nordenskioldii;* cone in cross-section (natural size). B, *Asplenium cascadia.* C, *Taxodium distichum miocenum.* (½ natural size.)

GENUS *Glyptostrobus*

Glyptostrobus ungeri (Heer)

Heer: *Flora Tert. Helvetiae*, I, 51; Taf. XIX, XX, Fig. 1; Taf. XLIX, Fig. 50. Newberry: (G. *Europaeus* Brogn.): 1. *Annals N.Y. Nat. Hist.*, IX (1868), 43.

2. *Illus. Cret. and Tert. Plants* (1898), Pl. XI, Figs. 6–8*a*.

3. *Later Extinct Floras of N.Am.*, p. 24; Pl. XXVI, Figs. 6–8*a;* Pl. LXV, Figs. 3–4.

No cones of this species were found, but the general form of these fragments is like the Figs. 1*e* and 1*a* of Taf. XX, and of Fig. 50 of Taf. XLIX of Heer. They also resemble quite closely those from Birch Bay, Washington, figured by Newberry (see 3 above) on Plate LV. Those were of Fort Union age.

GENUS *Taxodium*

Taxodium distichum Miocenum (Heer), Fig. 5, C; Fig. 7, D.

Heer: *Miocene Baltische Flora* (1869), p. 18; Taf. II, III, Figs. 6, 7.
Newberry: *Later Extinct Floras of N.Am.*, p. 22; Pl. XLVII, Fig. 6; Pl. LI, Fig. 3, in part; Pl. LII, Figs. 2, 3, 4; Pl. LV, Fig. 5.
Lesquereux: *Tertiary Flora* (1878), VII, 223; VIII, 73.

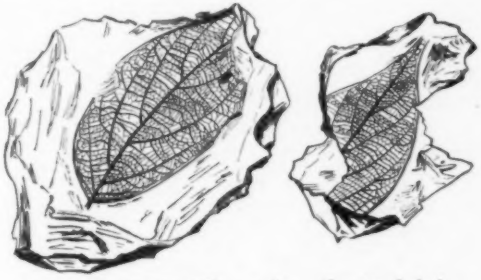

FIG. 6.—*Laurus cascadia* var. *leve*. (½ natural size)

FIG. 7.—A, B, B¹, *Laurus cascadia*. C, *Sequoia nordenskioldii*. D, *Taxodium distichum miocenum*. (½ natural size.)

The Cascade specimens are quite typical. The form is Greenland Miocene or basal Eocene in age.

GENUS *Sequoia*

Sequoia nordenskioldi (Heer) (Figs. 5, A, 7, C, 8, B)

Heer: *Flora Foss. Arct.*, II ("Miocene Spitzbergens," 1870), 36; Taf. II, Fig. 13*b*; Taf. IV, Figs. 1*a*, *b*, 4–38.
Newberry: *Later Extinct Floras of N.Am.*, p. 20; Pl. XXVI, Fig. 4.

Sequoia nordenskioldi is represented by a few leafy branches occurring with the *Taxodium*, but in addition by a handsome cone. The cross-section is given in Fig. 5. The form is referred to *S. nordenskioldi* rather than to *S. langsdorfii* because the leaves are very little if at all narrowed before they join and run down the stem. The cone is almost identical with that of Heer (*op. cit.*, Taf. IV, Fig. 4*a*), except that these dimensions are 20×22 mm., not 16×13 mm., as Heer gives, and that here no leaves remain on the branch. This cone is not as elongate as in *S. langsdorfii*.

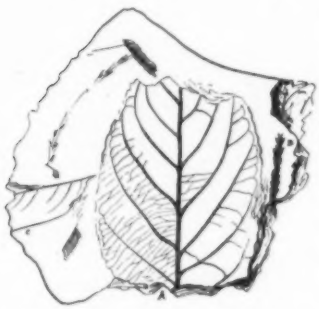

FIG. 8.—A, *Pterospermites whitei*. B, *Sequoia nordenskioldii*. C, *Sapindus obtusifolius*. (½ natural size.)

DICOTYLEDONS

There are no identifiable monocotyledons found in these beds. Dicotyledons are represented by ten fairly well-preserved forms, and by fragments of many more. The genera are: *Ficus*, *Juglans*, *Hicoria*, *Laurus*, *Magnolia*, *Populus*, *Protoficus*, *Pterospermites*, and *Sapindus*.

GENUS *Ficus*

Ficus ungeri (Lesq.)

Lesquereux: Supplement *Ann. Rept.*, 1871, p. 7; Fig. 1.
Hayden Survey, VII (1878), 195; Pl. XXX, Fig. 3.

Numerous fragments in F 831+ 50 beds are referred doubtfully to this form. The open-bowed secondaries in almost opposite pairs and the "very entire" margin are identical. Noted from Green River group, Middle to Upper Eocene.

Ficus sp. ? (Knowlton)

Knowlton: *Rept. on Fossil Plants Associated with Lavas of Cascade Range* (Western Oregon) (1898), p. 46; Pl. III, Fig. 1.

In shales (F 831+50) a specimen very similar to Knowlton's figure, in the roundly notched margin, and the 45° angle of emergence of the secondaries, was found. Here also no base or tip was to be seen.

GENUS *Hicoria*

Hicoria (Carya) *antiquorum* (Newb., Knowlton)

Newberry: *Ann. N.Y. Lyc. Nat. Hist.*, IX, (April, 1868), 72.
Illust. Cret. and Tert. Plants (1878), Pl. XXIII, Figs. 1–4.
Lesquereux: *Later Extinct Floras of N. Am.* (1868), p. 35, Pl. XXXI, Figs. 1–4.
Tertiary Floras (1878), VII, 289; Pl. I, Figs. 1–5; Vol. VIII, Pl. I, Fig. 2.
Knowlton: *Tertiary Plants of N.Am.* (1898), p. 117.
Fossil Flora of Yellowstone Park, etc.

This form is found in the sandy F 844 beds. It is referred to these species rather than to *Juglans nigella*, because the teeth are here rounded, as in *Hicoria*, and the secondaries are less prominent than in *J. nigella*. The leaf narrows gently toward the base and joins the stem (midvein) by a quarter-inch long winged "petiole." The form is noted by Newberry and by Knowlton from Eocene beds (*Planatus*) at the mouth of the Yellowstone River.

GENUS *Juglans*

Juglans acuminata (Heer)

Heer: *Flora Tert. Helvetiae*, p. 88; Taf. CXXIX, Figs. 2–8.
Flora Foss. Arct., VII, "Grönlands," 761; Taf. LXXV.
Knowlton: "Fossil Plants from Kukak Bay," *Alaskan Exp.*, IV (1904), 152; Pl. XXXIII, Fig. 3.

The form is identified from fragments only, but these are rather numerous. The entire margin and the angle of the midrib and secondaries are very similar in these specimens and in Heer's figures, but show considerable dissimilarity to Knowlton's type, where the angle between the midrib and secondaries is larger and where the latter are alternately long and short and bowed. The form, according to Heer, "is spread through the whole Tertiary and possesses many synonyms."

GENUS *Laurus*

Laurus cascadia N.Sp. (Figs. 6 and 7, A, B, B[1])

This specific name is given to several excellently preserved specimens in the shales of F 831. There is variation among the forms, but hardly more than to permit of naming of two varieties. The leaf is ovate lanceolate, coming to a sharp slender tip, and slightly unsymmetrical at the obtusely pointed base. There are six to eight pairs of strong secondaries, the members not directly opposite, besides a rather faint pair at the base, where the members are opposite. Secondaries come off at an angle of about 70° or less, as in Fig. 7, and are very gently bowed. The tertiaries show a horizontal parallel arrangement all the way across the leaf, so that they do not join the secondaries at right angles, except in the case of the two lower pairs. Fig. 6 shows preserved a fine network of veins between the tertiaries. The margin of the leaf is entire, and the ultimate veins border it in a series of loops. About one-quarter inch of petiole was found (Fig. 6). In Fig. 6 the breadth is 38 mm., the length probably 100 mm. The two pieces figured are not parts of one leaf. In Fig. 7 the dimensions are 32×80 mm., and here A and B are two sides of the impression of one leaf. A small form, very like Fig 6, but not drawn, was about 18×35 mm. *L. cascada* resembles *L. similis* of Knowlton (*Rept. on Fossil Plants Associated with Lavas of Cascade Range of Oregon*, Pl. V, Figs. 1 and 4) merely in the horizontal tertiaries and in the angle of the secondaries. Tip and base are, however, quite different in the two forms. The base of *L. perdita* comes nearest to being as blunt as that of *L. cascadia*.

Laurus cascadia leve var. *nova* (Duror) and *L. cascadia* (type) differ largely, in that the former is proportionately broader and with somewhat heavier veins.

GENUS *Magnolia*

Magnolia nordenskioldi (Heer)

Heer: *Flora Foss. Arct.*, VII, "Grönlands," 123; Taf. CVIII, Figs. 2, 3; IV. "Spitzbergens," 82; Taf. LII, Fig. 1.

This reference is made doubtfully on certain fragments from the sandstone of F 844. The size of the leaf, strength, and irregular

anastomosing of the secondaries of the veining are correct. The tertiaries, arising at right angles to the secondaries and dovetailing with the tertiaries from adjacent secondaries, are also similar to Heer's figures. The form is noted from the Canadian Miocene—really Eocene.

GENUS *Populus*

Populus is represented by numerous more or less fragmentary remains, in which, however, many of the characters are fortunately plainly discernible. Three of Ward's species are believed to be present, besides one of Heer's. The three forms are noted from beds called Laramie, now considered of Fort Union age.

Populus amblyrhynca (Ward)

Ward: *U.S.G.S. Bull. No. 37* (1887), 20; Pl. VI, Figs. 1–8.

Reference of the forms to this species is made with great certainty. In the Cascade form the base is somewhat flatter than in Ward's figure, the identification resting chiefly upon the character of the thick tertiaries sent out from the inner side of the second pair of secondaries. The resemblance is closest to Ward's Figs. 2 and 3 of Pl. VI.

Populus cuneata (Newb.)

Newberry: *Later Ext. Floras*, pp. 31, 64.
Illus. Cret. and Tert. Plants, Pl. XIV, Figs, 1–4.
Lesquereux: *Cret. and Tert. Floras*, p. 225; Pl. XLVI, Fig. 5.
Dawson: "Cret. and Tert. Floras of Brit. Col. and N.W. Terr.," *Trans. Roy. Soc. Can.*, Sec. IV (1882), p. 32.
Ward: *U.S.G.S. Bull. No. 37* (1887), p. 19; Pl. IV, Figs. 5–8; Pl. V, Figs. 1–3.

One specimen was so called because the first pair of secondaries here, as in the figures of *P. cuneata*, leave the midrib about 5 mm. up from the attachment of the petiole.

Populus zaddachi (Heer)

Heer: *Flora Foss. Arct.*, I, 98; Taf. VI, Figs. 1–4; II, 468; Taf. XLIII, Fig. 15*a*; Taf. XLIV, Fig. 6.
Flora Foss. Alaska, p. 26; Taf. II, Fig. 5*a*.
Lesquereux: *Mem. Mus. Comp. Zoöl.*, VI (1878), No. 12; Pl. VIII, Figs. 1–8.

This form is referred to this species because it is remarkable for its larger size. Judging from a fragment, the complete leaf was about 4×6 inches, as is that of Lesquereux in Fig. 8. There are three pairs of secondaries, the lowest very faint, the innermost very strong and straight. The margin is not preserved. Lesquereux notes this form from Upper Miocene, but one of Heer's examples is Miocene of Spitzbergen (equal to Eocene).

Populus artica (Heer)

Heer: *Flora Foss. Arct.*, IV, Taf. XXXII.

The Cascade form is very questionably referred to this species. There is a single smooth, faintly veined leaf from beds F 831+50 whose base is almost cordate but otherwise agrees with *P. artica*, and even similar bases are to be found in Heer's figures.

GENUS *Protoficus* (*Saporta*)

Protoficus is represented by many beautifully preserved specimens from shales of F 831+50. They are apparently all of one new species.

Protificus fossi N.Sp. (Figs. 9 and 10)

The leaf is lanceolate, broadest just at the middle; the apex is a short, sharp point; the margin is irregularly, sharply dentate to one-third of the way to the base, then wavy to crenulate. The base is blunt to slightly tapering and not absolutely symmetrical, as seen in Fig. 10. The midrib is straight and moderately strong, with seven pairs of secondaries. The members of each pair are not strictly opposite, except above, where they are strongly bowed outward. The nervation has a palmate aspect, since the two lowest pairs of secondaries come off at the top of the petiole, and the rest only above the lower half of the leaf, or even higher. Six pairs of tertiaries arise from the second pair of secondaries and form loops near the margin. Small nerves extend from these loops into the teeth. All the other tertiaries are at right angles to the midrib in parallel "horizontal" rows. One small specimen measured 11 cm. in length by 4.5 in breadth (Fig. 10); the type (Fig. 9) is 9 cm. in width by 15 cm. in length.

The tertiary veination is similar to that of *Ficus tiliafolia* and there is also something of the same palmate look; but in *Ficus* the gap to the next pair of secondaries is only one-third as exaggerated as here. The margin of *F. tiliafolia*, moreover, is entire.

Protoficus zelleri of Lesquereux (*Bull. Mus. Comp. Zoöl.*, XVI, No. 12 [1888], 50), while described as notably palmate, is more cordate at the base and the border is merely crenulate. This leaf is only 7×5.5 cm.

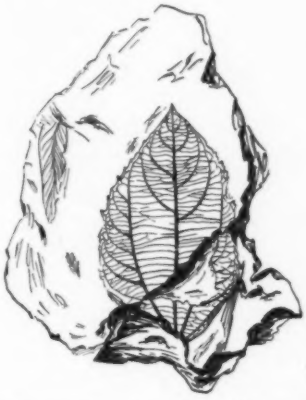

FIG. 9.—*Protoficus fossi.* (½ natural size.)

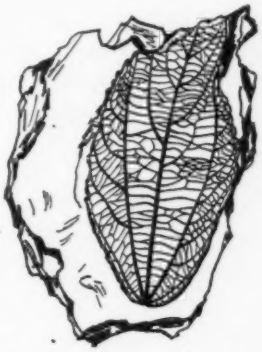

FIG. 10.—*Protoficus fossi.* (½ natural size.)

Protoficus inequalis (Newb.) (*Proc. U.S. Nat. Mus.* V [1882], 512) is not described as having a gap between the lower end and upper secondaries and is notably unsymmetrical at the base. The margin is merely undulate.

GENUS *Pterospermites*

Pterospermites whitei (Ward) (Fig. 8)

Ward: *U.S.G.S. Bull. No. 37* (1887), p. 94; Pl. XLI, Figs. 5 and 6.

The species from the shales of F 831+50 is in marked contrast to the foregoing *Protoficus*. The identification is rather certain, although the base and tip are wanting. The midrib is not quite so sinuous above as it is in Ward's figures. The form is noted

from the Laramie of Montana, now conceded to be Fort Union in age.

GENUS *Sapindus*

Sapindus obtusifolius (Lesq.) (Fig. 8C)

Lesquereux: *Hayden Surv.*, VII (1873), 266; Pl. XLIX, Figs. 8–11; VIII, 235; Pl. XLVIII, Figs. 5–7.
Knowlton: *U.S.G.S. Bull. No. 204*, p. 79.

The form is represented by numerous fragments such as are shown in Fig. 8, C. Better specimens (not figured) show the typical, unequal base and the alternately stronger and weaker secondaries. Similar forms are described by Knowlton from the Fort Union of Montana and North Dakota.

The writer wishes to express her indebtedness to Dr. Arthur Hollick of the New York Botanical Gardens for valuable help and suggestions.

REPORT ON THE FAUNA OF THE MALONEY SERIES

Rafinesquina (Hall) *deltoidea* (Conrad) (Fig. 11, A, B, C, D), *Leptaena deltoidea* Conrad, *Am. Geol. Rept.*, 1838, p. 115.
Strophomena deltoidea Davidson, *Foss. Brachiopoda*, III (1864–71); Pl. XLII, Figs. 1–5; Pl. XXXIX, Fig. 22.
Streptorhyncus (*Strophonella*) *deltoidea* (Hall, 1883), *Sec. An. Rept. State Geol. of New York*, Pl. XLII, Figs. 1–7.
Rafinesquina deltoidea Hall, *Pal. New York*, VII; Part. I, p. 281; Pl. IX*a*, Figs. 1–5. (Same figures as in references above.)

The Cascade specimens are referred with slight hesitation to *Rafinesquina deltoidea*, notwithstanding the fragmentary nature of the material. There is a strong resemblance to *Plectambonites* (*Leptaena*) *sericius* (Sow.) var. *rhombica*, as figured in Davidson's *Fossil Brachiopoda*, V, 169; Pl. XII, Figs. 4–7. However, the remains of the muscle scars, and more especially the concentric wrinkles, stronger near the hinge line, are characteristic of *Rafinesquina*. The alternate striation, such as the Cascade specimens show, is described in both forms, "every fifth or seventh striation markedly stronger." Here generally every fifth striation, though rarely every seventh, and occasionally every second, is emphasized. Such a variation, and another in the profile of the shell, is noted

by Professor M'Corq (quoted in Hall, *op. cit.*). In these specimens the most convex shell (Fig. 11, A, B) is not sharply flexed at any one point, while younger individuals, as in Fig. 11, C, show less arching, but a more sudden geniculation. The specimens are partly exfoliated and have a finely punctate surface.

Fig. 11, A, B, and D are of pedicle valves, and Fig. 11, C of a brachial valve. This last specimen is partly an impression of the

FIG. 11.—*Rafinesquina* (Hall) *deltoidea* (Conrad). A, B, and D, pedicle valves; C, brachial valve.

outer surface of the shell, since the striations show as grooves; but part of the true shell remains where the muscle scars are shown.

Illaenus americanus (Billings)

Billings (1859, quoted; 1865, quoted and figure copied): *Paleozoic Fossils*, I, 329; Fig. 316*a–d*.

Winchell and Ulrich: *Minn. State. Surv.*, III (1897), Part II, 714; Figs. (from above) 20, 21, 22, 23.

FIG. 12.—*Illaenus americanus* (Billings). A, front view; B, top view; C, side view.

A single specimen, the glabella and fixed cheeks, was found associated with the *Rafinesquina deltoidea*. All the features on these parts agree perfectly with Billings' figures. This specimen probably belonged to an animal one inch long, while Billings'

forms ranged from two to three inches in length. Naturally, smaller forms have been noted, as in Grabau and Shimer, *Index Fossils*, p. 295, where one and one-fourth inches is given as the entire length.

Fig. 12, A is the front, Fig. 12, B the top, and Fig. 12, C the side view of the one specimen. The dotted line in Fig. 12, B gives the outline of the eye, which was destroyed in uncovering the fossil.

Both of these forms are index fossils of Trenton age. Naturally, they are not restricted to one bed, but in no case have they been recorded as younger than Ordovician.

The writer is indebted to Dr. Shimer and to Dr. Grabau for valuable help and advice.

"PUFF" CONES ON MOUNT USU

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Two days before the eruption of Mount Usu, in southwestern Hokkaido, Japan, the writer arrived at the foot of the volcano. He remained there for twelve days, watching every phenomenon, going without sleep the first five days. The first explosion occurred

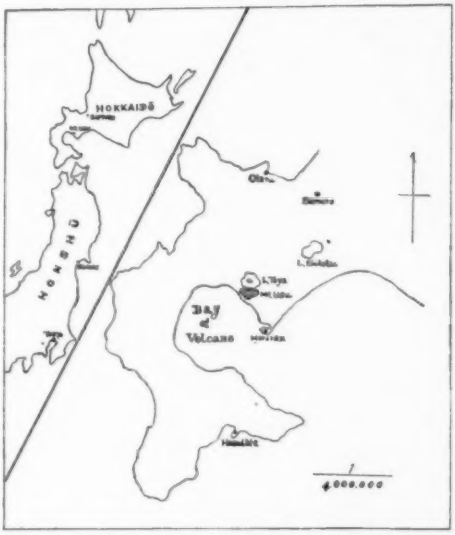

FIG. 1.—Sketch map of southwestern part of Hokkaido

on July 25, 1910, and others followed in rapid succession. Violent eruptions ceased in about ten days and the writer returned to Sapporo on August 7. He again visited the volcano in September and in December of the same year, in May and October, 1911, in

May, 1912, and in May, 1913. Many interesting facts were observed which will be published later in another paper. Here attention is to be called only to certain peculiar cones formed on one of the mud flows.

The main eruption of the volcano caused the formation of forty-five small explosion craters on its northern slope. These craters extend from east to west in two zones along Lake Toya,[1] north of the volcano. During the first few months after their formation innumerable bombs and considerable quantities of sand and ashes were blown from every craterlet. From five of them mud flowed at different times, the flow from a small crater at the southern foot of the parasite cone Nishi-Maruyam being especially interesting. This crater is located on a gentle slope of about five degrees, and is 100 meters in diameter. For twenty days it intermittently threw out columns of hot water, occasionally mingled with mud, to a height of about 60 meters. Approximately two hundred eruptions occurred per day at intervals of from three to thirty minutes. A mass of mud, estimated by the writer at 230,000 cubic meters, spread out in a sheet averaging 1.5 meters in thickness, over an area 200 by 700 meters. It covered a farm, where it destroyed a thousand apple trees and other crops, and pushed three houses in the direction of the lake and finally destroyed them.

The mud consists mainly of plagioclase, hypersthene, augite, magnetite, and hematite, and resembles the material of the sea sand at the west foot of Mount Usu. It differs, however, in also containing fragments, from the size of peas to that of nuts, of compact gray to coarse black andesite. These fragments are not usually exposed at the surface of the mud, having sunk on account of their greater size.

The materials thrown out by the crater were highly heated and sticky at the time of their eruption, and contained a great amount of water and gas. For several months the flow continued steaming, but as time passed and the moisture and gases became exhausted, it ceased, and the mass became harder and harder. A year after

[1] Lake Toya is a depression lake, according to T. Kato (*Report Earthquake Investigation Committee*, Vol. LXII).

the eruption the surface of the flow was so hard that it was difficult to discern footprints upon it, and specimens could be obtained only with the aid of a pointed stick or a hammer. At this time the surface was flat except for low, wavy undulations and very irregular sun cracks.

A year later the writer found the flow covered with thousands of small cones, each of which had an opening which was compara-

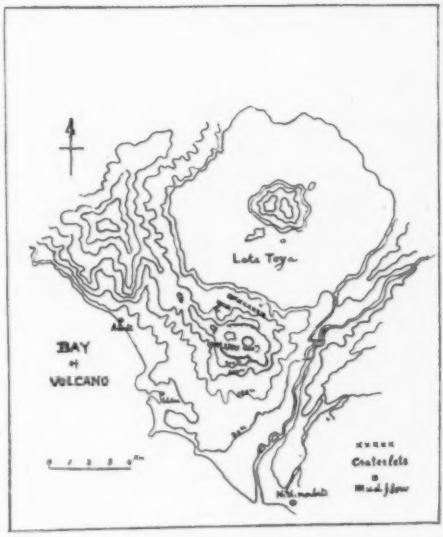

FIG. 2.—Map of Mt. Usu and vicinity, showing the position of craterlets and mud flow here described.

tively large but of no particular shape. The cones were of different sizes, the smallest being 0.5 meter in diameter and 0.1 meter in height while the largest was 3.0 meters in diameter and 1.5 meters in height. They were irregularly arranged on the flow at intervals of 10 to 30 meters, and were either dome-shaped or resembled a common bell with a slope of forty degrees.

The cause which produced these elevations is the same as that which forms small pitted cones when any viscous substance is boiled, namely, the escape of gases or vapors through the mass

and the breaking of the bubble at the surface. After the cessation of the mud flow the surface dried and sun cracks were formed. The gases near the surface rapidly escaped through these openings, but those imprisoned near the bottom of the mass were unable to do so, the upper part only having dried out. Later, by the coalescing of the small bubbles, the remaining gases united beneath the surface in reservoirs of greater size. The accumulated pressure finally became great enough to force a passage through the mud to the surface, the sudden escape of the gas forcing the mud upward

FIG. 3.—The largest "puff" cone. Photo taken by the writer, May 16, 1912

to form cones. The other mud flows in this district, being thinner, dried out more rapidly, and no cones were formed.

The writer has been unable to find descriptions of any such phenomenon in the case of other mud flows, although similar elevations occasionally occur on lava flows. He therefore suggests the name "puff cones."

No new cones were formed after the summer of 1912, the greater part of the gas having been expelled. Since that time weathering has begun to reduce the slopes, so that, in all probability, no trace of this fantastic phenomenon will remain after a few years.

ORIGIN OF FOLIATION IN THE PRE-CAMBRIAN ROCKS OF NORTHERN NEW YORK[1]

WILLIAM J. MILLER
Northampton, Massachusetts

INTRODUCTION

Data bearing upon the problem of the origin of foliation in the pre-Cambrian rocks of northern New York have been gathered during the last ten years by the writer while he was engaged in the geological surveys of various quadrangles in the Adirondack Mountain region. In the attempt to explain the origin of the foliated structures of the rocks, examples and analogies from other parts of the world will be introduced, and it is hoped that the conclusions reached may have a wider application than to the Adirondack region alone.

This paper is not much concerned with criteria for the determination of original igneous or sedimentary character of the rocks. The conclusions reached are almost wholly based upon observations made upon rocks which have been generally recognized as quite certainly either igneous or sedimentary. Rocks of rather doubtful origin are frequently met in minor quantity, but these may be disregarded in the present discussion.

The strata all belong to the very ancient Grenville series, including various gneisses and schists, together with crystalline limestone and quartzite. The chief criteria for the determination of their sedimentary origin are: distinct banded structures, often showing alternating layers of widely different composition sharply separated from each other; presence of extensive bodies of limestone and quartzite interbedded with the gneisses; dissemination of graphite flakes through many of the rocks; and the very common occurrence of garnet in many of the rocks, and the less common occurrence of sillimanite.

[1] Published by permission of the Director of the New York State Museum.

The metamorphic rocks of igneous origin, given in regular order of geologic age, comprise the anorthosite series, the syenite-granite series, and the gabbros, all of which show quite varied degrees of metamorphism. All are intrusive rocks and younger than the Grenville. Among the criteria for recognizing their igneous origin are: preservation of original rock textures, such as the porphyritic and the diabasic; relative homogeneity in large bodies; common occurrence of distinct inclusions of older rocks; intrusive contacts, often with dikes from the large bodies penetrating the older rocks; very common occurrence of zircon and zoisite in fresh, well-crystallized grains.

THE GRENVILLE AND ITS FOLIATION

FOLDING OF THE GRENVILLE

Character of the Grenville series.—The Grenville series comprises the oldest rocks of the Adirondack region, and they are, in fact, among the most ancient known rocks of the earth's crust. They consist of a great mass of thoroughly crystallized sediments, such as limestones, sandstones, and shales which have been changed to crystalline limestones, quartzites, and various gneisses and schists. A more or less well-developed foliation is always parallel to the stratification surfaces which are usually distinctly preserved in spite of the crystallization. Granulation is not common. Grenville strata are well represented throughout the Adirondack region, their distribution being very irregular or "patchy" in small to large areas. They are considerably less extensive than the later (intrusive) syenite-granite series, which latter, together with the Grenville, makes up the great bulk of Adirondack rocks. Neither top nor bottom of the Grenville series is known, though thicknesses of from 10,000 to 20,000 feet are actually shown in single sections, and the total thickness is doubtless much greater. Adams and Barlow report a Grenville section about eighteen miles thick in Ontario. The strata are often tilted at high angles or very moderately folded, and sometimes locally contorted. There is a general tendency toward a northeast-southwest strike of Grenville masses in the Adirondacks, but there are many important exceptions.

Grenville series generally regarded as highly folded and compressed.—It has been quite generally assumed by all (including the writer) who have carried on geological work in the Adirondack region that the Grenville strata have been severely compressed and folded as well as thoroughly metamorphosed and foliated by the compression. A few citations from the more recent publications will illustrate the ideas usually held. "There is abundant proof that the rocks have undergone great compression and have been folded and faulted on an extensive scale."[1] The Grenville rocks "have been greatly compressed and intricately folded and plicated."[2] "The old sedimentary rocks have undergone complete recrystallization, entirely obliterating their old textures, and, as a result of severe compression, have had a development of cleavable minerals along certain parallel planes, the mineral particles having a common orientation."[3] "In pre-Potsdam time the pre-Cambric sediments had been tremendously folded and faulted and intruded at great depths."[4] "After the intrusions the whole region was subjected to intense compression and metamorphism when the gneissic or foliated structure of all the rocks was developed."[5]

An alternative hypothesis.—That the Adirondack Grenville strata are more or less folded is admitted at the outset, but, in the light of recent studies, the writer doubts the interpretation of the folded, tilted, and foliated structures as due to intense lateral compression. Certain evident features of the Grenville strata and related intrusives are directly opposed to this interpretation, while all of the structural features may be much more satisfactorily explained in another way. Thus it is conceived that the originally horizontal, or at most only very moderately folded, Grenville strata were much broken up and tilted in masses great and small, and in other cases actually domed, by the irregular upwelling of the great bodies of magma (especially syenite-granite) under only very moderate lateral pressure. This alternative explanation will be

[1] D. H. Newland, *New York State Mus. Bull.*, No. 111, 1908, p. 20.

[2] H. P. Cushing, *ibid.*, No. 145, 1910, p. 9.

[3] *Ibid.*, No. 95, 1905, p. 400.

[4] I. H. Ogilvie, *ibid.*, No. 96, 1905, p. 478.

[5] W. J. Miller, *ibid.*, No. 170, 1914, p. 77.

developed at some length in its application to the Adirondack region.

Evidence against intense folding of the Grenville.—In spite of the assumption of severe lateral compression, no large-scale example of intense folding of the Grenville has ever been positively demonstrated in the Adirondacks, and this in the face of the fact that many hundreds of square miles have been mapped in detail. Describing the Grenville structures of the Elizabethtown–Port Henry quadrangles, Kemp says: "The dips are prevailingly moderate and the ancient sediments appear to have been folded or tilted to only a moderate degree."[1] Regarding the Long Lake quadrangle, Cushing says: "Nearly east and west strikes prevail, and the prevalent dip is southward. This either indicates comparatively little folding, or else isoclinal folding, or else that the foliation does not coincide with the bedding and so does not bring out the folding. It is not possible to demonstrate which of these alternatives is the true one, though the second is very unlikely, and all the direct evidence obtainable is against the third."[2] He also states that in the largest Grenville belt "the dips are so flat that they can seldom be made out with certainty."

The writer[3] has described a structure section in the Broadalbin quadrangle four miles long across the strike of Grenville strata with dips of 20–30° to the southeast. The exposed thickness of Grenville is about 10,000 feet with no repetition of beds due to possible isoclinal folding and no field evidence for profound faulting. Another Grenville section recently described by the writer[4] in the North Creek quadrangle is five miles long with a pretty uniform dip of from 40° to 50°, thus showing a thickness of some 18,000–20,000 feet of strata. There is no evidence of repetition of strata by either folding or faulting. The Grenville is extensively developed throughout this quadrangle, and all the available evidence points to only moderate deformation of the strata either by tilting or slight folding.

[1] J. F. Kemp, *New York State Mus. Bull.*, No. 138, 1910, p. 85.

[2] H. P. Cushing, *ibid.*, No. 115, 1907, p. 485.

[3] W. J. Miller, *ibid.*, No. 153, 1911, p. 13.

[4] *Ibid.*, No. 170, 1914, p. 15.

According to Cushing, "the foliation strike over much of the Saratoga quadrangle is nearly east-west, and the dips are to the south and rather flat, seldom reaching 45°. As elsewhere, a great monocline of the rocks is suggested, and, as elsewhere, this makes a Grenville succession of enormous thickness, so thick as to suggest caution in the interpretation of the structure, and as to emphasize the probability of the alternative suggestion that the rocks are closely pinched and folded in a series of closed, overturned folds."[1] It is, however, by no means necessary to assume that such common occurrences of monoclinal dips may be due to isoclinal folding. The breaking up and tilting of many blocks or belts of Grenville strata into general parallelism with the upwelling bodies of magma could quite conceivably have taken place under only very moderate lateral compression at most, and, in such cases, monoclinal dips are just what would be expected. This matter will be more fully discussed below.

In the Little Falls, Remsen, Port Leyden, and Lake Pleasant quadrangles, which are also mapped in detail, the Grenville is only sparingly represented, but none of the field evidence points to profound folding of the strata due to lateral compression.

The recent (1913–14) survey of the Blue Mountain quadrangle by the writer has thrown important light on the structure of the Grenville series which is there extensively represented. The great Panther-Snowy mountain mass (altitude 3,900 feet) of syenite occupying the southern portion of the Blue Mountain and the northern portion of the Indian Lake quadrangles is completely bounded on the west, north, and northeast by an unbroken belt of Grenville (mostly limestone) whose strikes and dips show it to lap up on the flanks of the mountain mass of igneous rock for many miles. The curving strike of the igneous rock is also essentially parallel to that of the Grenville. It is evident that we have here a large-scale example of the raising or doming of Grenville over the surface of the great body of uprising magma, the general cover having been removed by erosion, leaving only the circumferential belt of Grenville strata. The higher portions of the syenite now rise fully 2,000 feet above the Grenville. This large-scale tilting

[1] H. P. Cushing, *ibid.*, No. 169, 1914, p. 30.

of Grenville strata is certainly not due to severe lateral compression, nor is there, in any part of the quadrangle, evidence of highly folded or compressed Grenville strata.

In the northwestern part of the Thirteenth Lake quadrangle the writer has examined Chimney Mountain, which is a mass of granitic syenite rising fully 900 feet above a valley on the west. Perfectly bedded Grenville rocks with dip of 50° lap over the whole western face of the mountain of igneous rock, and it seems certain that the tilt of the strata was produced by the rise of the magma.

We are thus led to conclude that none of the published Adirondack geologic maps or available data afford any reason to believe that the Grenville strata were ever profoundly folded or compressed. There is, however, much tilting on large and small scales and some very moderate folding. Such structures may be readily accounted for simply by the irregular intrusion or upwelling of great bodies of more or less plastic magma which broke up, tilted, and lifted or domed the masses of Grenville.

Grenville structure in the Thousand Islands and Ontario regions.—The Thousand Islands district forms the connecting link between the Adirondack and Canadian pre-Cambrian areas, and lies to one side of the region discussed in this paper. Having recently studied the Thousand Islands district, Cushing says: "The Grenville beds are now found for most part in highly inclined condition, dips of less than 45° being relatively rare, while those approaching verticality are common. . . . . It has also been shown that the dip is not everywhere in the same direction, but that, with the general direction of strike to the northeast-southwest, the dip, while prevalently to the northwest, becomes at times southeast. . . . . The highly tilted condition of the rock series, and the changing dips seem certainly indicative of folding."[1] He then describes a prominent belt of Grenville strata which he believes has a synclinal structure. But, accepting the existence of this syncline, does such a structure prove the region to have been subjected to an intense force of compression? Large bodies of granite bound this Grenville belt on either side, and it is quite conceivable that the uplifting effect of the intruding masses, possibly accom-

[1] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 109.

panied by some crowding or squeezing of the Grenville between the igneous masses, may have produced this very structure. Cushing also argues that "the general parallelism of the foliation of all the pre-Cambric rocks" affords "evidence of thoroughgoing compression of much later date" than the granitic intrusions. But, as will be shown below, such parallelism of foliation is not necessarily due to severe lateral compression. It should be said, however, that in the Thousand Islands region the granitic and Grenville rocks do seem to be more strikingly arranged in parallel northeast-southwest belts than is usual throughout the Adirondacks. It is possible that considerable orogenic forces did operate across the area from the Thousand Islands region northward into Canada, where also the parallelism is notable. Recent study of the Canton quadrangle seems to indicate considerable folding there. Adams and Barlow, in their description of the Haliburton and Bancroft areas, state that the batholiths "are elongated or arranged in lines having a prevailing direction of about N. 30° E., to which direction the strike of the rocks (Grenville) lying between the batholiths in general conforms. This direction constitutes, so to speak, the general strike of the country, and shows that its present structure has been determined, not only by the rise of granite magma, but by the presence of a second factor in the form of a tangential pressure, acting simultaneously."[1] But it is not at all certain that this tangential pressure was really orogenic in character. Even a very moderate compressive force, not at all sufficient thoroughly to fold and plicate the rocks, acting upon the rising magmas would readily account for all the structural phenomena now visible.

Variation of foliation strikes.—Even if we grant a very considerable lateral compression in the Thousand Islands–Canadian region, the Adirondack area, fully a hundred miles across and to the southeast, does not necessarily come under the same category. In fact, while parallelism of syenite-granite and Grenville rock belts and foliation are common in the Adirondacks, there are so many important variations from a northeast-southwest strike that any generalization regarding such a strike of the rock belts is of little

[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 16.

significance. A glance at the accompanying sketch map (Fig. 1) will emphasize the fact that various large areas show strikes distinctly out of harmony with a northeast-southwest structure. The unpublished Lake Placid geologic map shows exceedingly variable strikes. Many variations also occur within most of the other quadrangles, more especially the North Creek, Long Lake, and Blue Mountain (unpublished). Within the Lake Pleasant quadrangle, the foliation strikes relatively uniformly northwest-

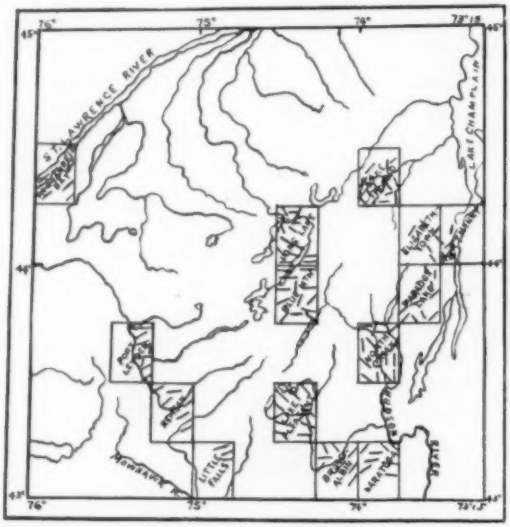

FIG. 1.—Sketch map of the Adirondack region showing generalized strikes of foliation within those quadrangles which have been mapped in detail.

southeast or just at right angles to the assumed force of compression of the region. Papers by Professor Kemp and assistants in the thirteenth, fifteenth, seventeenth, eighteenth, and nineteenth annual reports of the New York state geologist contain many very variable strike observations in the eastern Adirondacks aside from the quadrangles of the accompanying sketch map. It thus seems clear that the Adirondack rocks show strikes which could not possibly have been produced by a severe lateral pressure exerted across

the whole region, for any such pressure, great enough to produce close folding, would have produced a high degree of parallelism of strikes throughout the region.

Local contortions.—Local contortions or sharp folds in the Grenville strata are by no means uncommon, being especially prominent in the limestones and closely associated hornblende and pyroxene gneisses. Such plications have usually been regarded as strong evidence for large-scale folding, being thought of as minor folds superimposed upon large-scale folds. Now, in the first place, it is the writer's experience that such local contortions or plications are very largely confined to the limestone beds, which are easily the most plastic of all Adirondack rocks. In the second place, the crowding of a batholithic magma against the invaded Grenville strata, or the catching of a mass of Grenville between two batholithic magmas, would readily account for more or less local contortions or even puckering of strata without any assumption of orogenic or severe lateral pressure exerted throughout the region. The shouldering action of the upwelling magmas must have produced rather severe local pressures. Regarding the Glamorgan batholith of Ontario, Adams and Barlow say that the Grenville rocks forming the periphery on several sides, "being squeezed between this and the adjacent batholiths, are too highly contorted . . . . to display the prevailing dip distinctly."[1] Evidently such structures do not necessarily call for severe regional compression.

Summary.—To summarize, there is no known evidence within the Adirondack region that the Grenville strata have ever been highly folded or severely compressed, while many broad Grenville belts are known to be only very moderately folded, and many masses, large and small, are merely tilted or domed at various angles. Very locally the strata are sometimes contorted or plicated. The structural relations are therefore best explained as having been the result of slow irregular upwelling of the more or less plastic magmas, probably under very moderate compression, whereby the Grenville strata, previously deformed very little or none at all, were broken up, tilted, and lifted or domed. The stratification surfaces of the Grenville were thus swung into general parallelism

[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 15.

with the slow-moving magmatic currents. According to this view, individual large blocks or belts of Grenville strata, or several such blocks or belts separated by intrusive masses, with strike of intrusive masses parallel to Grenville stratification, would be expected to show monoclinal dips; some Grenville masses were shifted around in irregularly rising magmas so as to show various strikes according to directions of movement of the magmas, and hence would not be expected to exhibit monoclinal dips; some Grenville masses were merely domed over bodies of rising magma and would exhibit more or less quaquaversal strikes and dips; while still other Grenville masses were probably bent or even considerably folded into synclines by being caught between bodies of magma upwelling at about the same rate. Isoclinal or close folding on a large scale would scarcely be expected.

In all of this discussion it is important to bear in mind that the Adirondack intrusives occupy a much greater extent than the invaded Grenville rocks, and that, in spite of their intrusive character, they everywhere seem to occupy the position of a fundamental or underlying gneiss. It appears to have been literally true that the Grenville strata were irregularly floated on a vast body of magma, the magma in many places having either arched up or broken through the strata.

ORIGIN OF GRENVILLE FOLIATION

We have just shown that the Grenville strata have never been highly folded or compressed. It is therefore necessary to explain the metamorphism of the strata on some other basis than that of subjection to severe lateral pressure. The old sediments are thoroughly crystallized, and it is certain that they have been reorganized into new minerals under deep-seated conditions; that is to say, they have undergone anamorphic metamorphism. But evidently we are here dealing with a case of essentially static, rather than dynamic, metamorphism.

Origin of parallelism of Grenville foliation and stratification.—The universal parallelism of Grenville foliation and stratification is a fact of prime importance. If the Grenville and accompanying great intrusives had been subjected to compression severe enough

to develop the distinct foliation, is it not remarkable that the stratification surfaces have never been obliterated and cleavage developed instead, and also that the stratification and foliation are always parallel? Now, the stratification of the highly crystalline Grenville is remarkably well preserved. Also, unless we assume intense isoclinal folding, so that mineral elongation could everywhere have taken place at right angles to the direction of lateral pressure, the parallelism of stratification and foliation cannot be accounted for by crystallization under severe lateral pressure. We have already shown, not only that there is no positive evidence for such isoclinal folding, but also that there is much positive evidence against any more than the tilting, or, at most, very moderate folding, of the Grenville on large scales.

Again, if the foliation of the Grenville were essentially a dynamic process—that is to say, the result of regional compression after the great igneous intrusions—why should the Grenville be notably less foliated and granulated than the intrusives? (See below.)

We are thus forced to the only alternative conclusion, namely, that the Grenville foliation was developed during the crystallization of essentially horizontal strata under heavy load of overlying material. Those minerals which cause the foliation were elongated during crystallization under heavy downward pressure where conditions of warmth and moisture were also favorable. According to this conception the parallelism of foliation and stratification is precisely what would be expected. It is quite generally assumed that static pressure, that is to say, simple downward pressure, "to the amount exerted in the upper part of the earth's outer crust, appears to have little metamorphic effect."[1] In dealing with the very ancient Grenville, however, it must be remembered that the material now at the surface was once very deeply buried. The thickness of the Grenville series in the Adirondacks is at least some miles and more than likely many miles. Adams and Barlow[2] have recently estimated a thickness of nearly eighteen miles for the Grenville strata in Ontario. It is also definitely known that during pre-Cambrian time the Grenville strata were subjected to tre-

[1] L. V. Pirsson, *Rocks and Rock Minerals* (1909), p. 335.

[2] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 33.

mendous erosion when at least some miles, and quite possibly many miles, in thickness of materials were removed. Thus it seems clear that much of the Grenville rock now visible was once far more deeply buried than any known body of sediments since the beginning of the Paleozoic. Conditions of downward pressure and temperature were, therefore, more than usually favorable for static metamorphism. On the basis of static metamorphism it is not necessary to account for a high degree of metamorphism, because the Grenville series, though thoroughly crystalline, is mostly only moderately foliated with relatively little granulation, and with stratification generally well preserved. It may also be suggested as a possibility that actual crystallization did not begin until an early stage in the intrusion of the slowly upwelling magmas when additional heat for regional metamorphism was supplied.

Evidence from other sources.—Experimental evidence is also suggestive in this connection. Thus, Becker and Day[1] have proved that crystals in general have a strong tendency to grow (or elongate) most rapidly at right angles to the direction of pressure. According to Wright,[2] cubes of glass formed by melting together wollastonite, diopside, and anorthite heated to the state of incipient crystallization under vertical pressure, showed, under the microscope, that the three minerals crystallized with long axes at right angles to the direction of pressure. Experimental evidence, therefore, strongly supports the possible development of elongated crystals in the Grenville sediments under conditions of static metamorphism.

Van Hise has suggested, regarding the parallelism of foliation and bedding in the Grenville series, that "vertical shortening and consequently horizontal elongation below the level of no lateral stress may have *begun* the process."[3] The writer views this as essentially the *whole* process, instead of assuming, as Van Hise did, that foliation parallel to bedding continued to develop under certain peculiar conditions when the rocks were subsequently folded. The explanation of foliation parallel to bedding is greatly simplified when it is not necessary to consider severe compression of the region.

[1] Becker and Day, *Proc. Wash. Acad. Sci.*, VII (1905), 283–88.

[2] F. E. Wright, *Am. Jour. Sci.*, 4th series, XXII (1906), 226.

[3] C. R. Van Hise, *U.S. Geol. Surv., 16th Ann. Rep.*, Part I, p. 773.

Describing the metamorphism of the Shuswap pre-Cambrian series in the Canadian Rockies, Daly says: "It is clear that the Shuswap series has not been seriously affected by dynamic metamorphism. The strata and most of the injected granites were completely or almost completely recrystallized while the strata lay nearly flat. In some localities the effects of dynamic metamorphism have been superposed on those due to previous static metamorphism."[1]

Orientation of Grenville inclusions.—Another fact of importance in connection with the origin of Grenville foliation is the occasional occurrence of well-foliated inclusions of Grenville gneisses variously oriented in the great intrusive bodies. Twenty years ago, in St. Lawrence County, Smyth, noting irregular inclusions of black gneiss in granite, said: "The two foliations, that of the black masses and of the (granite) gneiss, range from parallel with, to perpendicular to, each other."[2] He also noted a similar arrangement of Grenville laminated gneiss inclusions in syenite in Jefferson County. The writer has observed similar phenomena on small and large scales at various localities. Kemp has recently noted inclusions in massive anorthosite and says: "The foliation of the fragments runs in all directions, even in an area of a few square yards. The inference is drawn that the Grenville gneisses were already strongly metamorphosed when the anorthosites entered."[3] It is thus clear, in spite of the usual assumption to the contrary, that the foliation of the Grenville could not have been the result of lateral pressure brought to bear after, or even during, the intrusion of even the oldest of the great igneous masses.

General absence of granulation.—Another fact favoring a process of essentially static metamorphism as opposed to that of dynamic metamorphism is that the Grenville gneisses are, as a rule, comparatively little granulated. Some rather local granulation is to be expected because of magmatic movements, especially where Grenville masses have been crowded against the upwelling magmas. The great intrusive syenite-granite series is very notably more

[1] R. A. Daly, *Geol. Surv. Can., Transcont. Excur. C 1, Guidebook 8,* 1913, p. 132.

[2] C. H. Smyth, *15th Ann. Rep. New York State Geologist,* 1895, p. 491.

[3] J. F. Kemp, *Geol. Soc. Am. Bull.,* XXV (1914), 47.

granulated than the Grenville series. How is this fact to be explained if both series have been subjected to strong regional compression after the intrusions?

THE SYENITE-GRANITE SERIES AND ITS FOLIATION

Character of the syenite-granite series.—The main bulk of syenites and granites in the Adirondacks are regarded by the writer as facies of a single great body intrusive into the Grenville, the intrusives being much more extensively exposed than the Grenville. Perfect gradations from basic (dioritic) facies of syenite to true granite are commonly shown, a quartz syenite being the prevailing rock. As regards granularity, structure, and mineral composition, the members of the syenite-granite series are very variable. The granularity ranges from fine to coarse grain, with medium grain decidedly prevalent. A porphyritic texture is sometimes well developed. Granulation is common, especially in the more acidic rocks, the feldspars generally being notably more crushed than the other minerals. In structure the rocks range from very faintly gneissoid to very clearly gneissoid or sometimes almost schistose, the foliation being accentuated by the roughly parallel arrangement of the dark-colored minerals. The minerals, especially quartz and feldspar, often show more or less flattening or elongation parallel to the foliation. In general the more highly foliated rocks appear to be most granulated. In mineral composition the range is from dioritic types rich in plagioclase, orthoclase, pyroxene, and hornblende; to syenite rich in microperthite, orthoclase, and hornblende or augite together with some quartz and plagioclase; to granite rich in microperthite, quartz, orthoclase, and microcline together with some plagioclase, hornblende, and biotite. Various accessory minerals in smaller amounts also occur. The color of the typical fresh syenite is greenish gray which weathers to light brown, while the fresh granite colors vary from greenish gray to light gray and pinkish gray to almost red. In common with the Grenville, the syenite-granite foliation shows a tendency toward a northeast-southwest strike, with parallelism of syenite-granite and adjacent Grenville quite common, though there are many notable exceptions.

Northeast-southwest structure of rocks.—We have shown that the Grenville series has never been closely folded or severely compressed, and that its foliation was not caused essentially by lateral pressure. The syenite-granite masses, being younger than an intrusive into the Grenville, cannot, therefore, have had their foliation developed chiefly by lateral pressure, though the probable existence of a very moderate lateral pressure is admitted.

In spite of many important exceptions, there is some tendency toward a general parallel northeast-southwest to east-west strike of Adirondack rock masses (Grenville and syenite-granite) and foliation. One view, clearly stated by Cushing, is that "since the rock [granite] solidified it has been subjected to compression, together with the Grenville rocks, giving to each a foliation parallel to the other, and elongating the batholiths in a northeast-southwest direction."[1] At another place he refers to this compression as "thoroughgoing" and of much later date than the granite intrusion. Cushing suggests the possibility of the development of "a similar and parallel foliation"[2] during the solidification of the batholiths due to their shouldering pressure exerted upon the adjacent rocks during the intrusion, but he says that if any such foliation developed it was obliterated by subsequent compression.

The writer's view is that the general northeast-southwest structural parallelism was brought about by just enough tangential compression to control the general directions of the upward-moving batholithic magmas. Accordingly, the intrusive bodies were more or less elongated during the process of intrusion, and there must have been a strong tendency for large and small bodies of previously horizontal, or only slightly deformed, Grenville strata to have been caught up and arranged with their long axes and foliation parallel to the magmatic currents, while the foliation of the intrusives would also have developed, as a sort of flow structure under moderate pressure, parallel to the magmatic currents. This pressure was doubtless in part due to the shouldering effect of the intrusives upon the adjacent rocks. In other words, the syenite-granite gneisses are "primary gneisses." Thus we should

[1] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 10.

[2] *Ibid.*, No. 145, 1910, p. 102.

expect a general northeast-southwest strike of both rock masses and foliation of Grenville and intrusives to be of common occurrence.

A statement made by Smyth twenty years ago regarding black gneiss inclusions in the syenite-granite series of St. Lawrence County is significant in this connection: "The parallel arrangement of the neighboring bands [inclusions] doubtless results from currents in the molten magma, which would tend to produce such a result. It is probable that the breaking into blocks resulted, in part, from strains applied after the magma was in a pasty and partially crystallized state. The blocks were more or less widely separated, and the intervening space was filled by the magma which flowed around the blocks without destroying their angular contour, and, at the same time, often produced an obscure flow structure in the gneiss parallel to the sides of the inclusions."[1] The bandlike inclusions here described by Smyth are seldom more than a few rods long, but the writer believes the principles set forth are applicable on a much larger scale throughout the Adirondack region.

Such parallelism of structural features does not, therefore, demonstrate that the rocks have been thoroughly compressed subsequent to the syenite-granite intrusions. The northeast-southwest structural features here referred to are more pronounced in the Thousand Islands region than is usual throughout the Adirondacks, and this may be readily explained by granting somewhat greater lateral pressure during the intrusion in the first-named region. In any case it is necessary to assume only very moderate compression—far less than would have been necessary to elongate the batholiths and develop distinct foliation in them after their complete solidification.

Exceptions to northeast-southwest structure.—There are many exceptions to the general northeast-southwest structural arrangement, and these prove that no severe tangential compression could ever have been exerted throughout the region after or during the intrusions. Among such exceptions are sharp variations in strike of groups of inclusions of well-foliated Grenville gneiss in the intrusives. Examples have already been cited. If the whole region has been subjected to compression thoroughgoing enough to flatten

[1] C. H. Smyth, *15th Ann. Rep. New York State Geologist*, 1895, p. 491.

out batholiths and develop foliation after the consolidation of the magmas, how are these sharp variations in strike of Grenville inclusions to be accounted for? According to the writer's view, such inclusions present no difficulties, because their foliation was produced prior to the intrusions, and some fragments, especially those caught up late in the stiff, nearly consolidated magmas with poorly defined currents, would not have been swung into parallelism in the uprising magmas.

Also there are important exceptions to parallelism of foliation of adjacent syenite or granite and Grenville gneisses in relatively large areas. A few examples will suffice: eastern side of Port Leyden quadrangle where Grenville with north-south strike is surrounded with syenite with strike N. 30° E.; northwest corner of North Creek quadrangle (see geologic map); near northeast corner of Lake Pleasant quadrangle (see geologic map); northwest of Indian Lake Village; one mile west of Long Lake Village; and in the Broadalbin quadrangle where the large areas of Grenville and adjacent syenite-granite show very different strikes. If the foliation has been produced by compression after the intrusions, how are such sharp differences in strike to be accounted for? Granting the writer's conception that the Grenville was foliated prior to the intrusions, and that the syenite-granite foliation was the result of magmatic flowage, it is to be expected that the magmatic currents would occasionally have broken across the Grenville and its foliation.

Very strong evidence against the development of foliation by compression of the great intrusives is the frequent occurrence of sharp variations in the strike of the foliation, often within short distances. Examination of the Long Lake, North Creek, and Lake Pleasant geologic maps, upon which foliation strikes are plotted, shows many strikes in granite or syenite ranging from parallel to right angles to each other, often within distances of a mile or two. Similar foliation variations occur upon the writer's Blue Mountain and Lake Placid geologic maps, not yet published. How can such foliation variations possibly be explained as due to lateral pressure? If due to compression of the whole region, should not the foliation always strike essentially at right angles to the compressive force?

If, however, we regard the foliation as essentially a sort of flow structure, such phenomena are readily accounted for as due to local variations in the magmatic currents.

Curving strike of foliation.—Still another piece of evidence, though less commonly shown, is the existence of certain broad, sweeping curves in the foliation of syenite or granite. The North Creek, Lake Pleasant, and Long Lake geologic maps show such features. When larger areas of the Adirondacks are mapped in detail, it is probable that more and better examples will be brought to light.

An excellent case of curving of foliation on a large scale is in the Panther-Snowy mountain mass above described as extending nearly across the southern portion of the Blue Mountain sheet and the northern portion of the Indian Lake sheet. The great mass of syenite shows an almost perfect radiation of foliation dips from its center toward the west, north, and east. The only reasonable explanation of such an arrangement of dips is that the foliation was produced as a flow structure in the uprising magma, the most rapid currents having been toward the center of the mass. In the writer's opinion, such a large-scale curved arrangement of foliation strikes and dips not only cannot possibly be explained as due to lateral pressure, since the foliation would then everywhere be practically at right angles to the pressure, but also conclusively proves that no severe compression ever affected the syenite.

Nearly thirty years ago, in his study of the Rainy Lake region, Lawson described a somewhat similar curved foliated structure in granite gneiss and said regarding its origin: "The simplest explanation that suggests itself to account for the structure is that of an uprising force acting on a plastic mass (pasty magma), such force acting with greatest intensity in the vertical line which would correspond to the axis of the cone or dome."[1]

A similar type of structure appears to be common in the Haliburton-Bancroft area of Ontario as described by Adams and Barlow, who say: "Within the batholiths themselves the strike of the foliation follows sweeping curves, which are usually closed and centered about a certain spot. . . . . From these central areas

[1] A. C. Lawson, *Ann. Rep. Geol. Surv. Can.* (N.S.), III (1887–88), 116.

of flat-lying gneiss the dip . . . . is generally outward in all directions. The batholiths, therefore, are undoubtedly formed by an uprising of the granite magma, and these foci indicate the axis of greatest upward movement, and those along which the granite magma has been supplied most rapidly."[1]

There are not only important variations from the general northeast-southwest arrangement of the region within the quadrangles themselves, but also much broader variations shown by a comparison of the average foliation strikes of all the quadrangles of the Adirondacks which have been mapped in detail. This is graphically presented by the accompanying sketch map. Such marked differences in foliation directions on large scales throughout the Adirondacks is certainly incompatible with any idea of thoroughgoing compression of the region. Thus in the Lake Pleasant, North Creek, Blue Mountain, and Saratoga quadrangles the foliation, either wholly or largely, strikes at high angles across the general northeast-southwest strike of the region, while in the Lake Placid quadrangle the strikes are exceedingly variable. If due to compression, the foliation strikes would be much more nearly northeast-southwest than they actually are.

Flow structure character of foliation.—Another significant feature of the foliation should be mentioned, namely, that, while all the minerals are arranged with long axes roughly parallel to the direction of foliation, the dark-colored minerals which accentuate the structure most often appear as narrow, irregular, wavy streaks which are seldom continuous for more than a few inches or a foot. In the writer's experience this type of foliation is by far the most common in the syenite-granite series, and it is believed to be the result of magmatic flowage. Lawson has noted an exactly similar phenomenon in certain granite gneisses of the Rainy Lake region of Ontario and says: "The lines of streaking are very often not straight but are wavy or contorted, sometimes intricately so, and are evidently due to flow movements in the magma prior to its final consolidation."[2] As already suggested, flow structures are locally

[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 14.

[2] A. C. Lawson, *Geol. Surv. Can., Mem. 40*, 1913, p. 93.

very distinctly developed, especially around some of the inclusions in syenite or granite.

Differences in degree of foliation.—Another important consideration is the frequent pronounced variation in degree of foliation in the rocks of the syenite-granite series. They are mostly distinctly gneissoid, rarely so much so as to be almost schistose, while in other cases they are so faintly gneissoid as to be practically massive. A striking feature is the frequent rapid change within a few rods or yards, from rocks which are very clearly gneissoid to others in which the foliation is scarcely discernible. Sometimes, within a foot or two, a very gneissoid zone lies between others which are only moderately foliated. In many cases there is no evidence whatever of shearing to account for these variations. It seems impossible to conceive that such abrupt foliation changes could ever have been produced by severe compression of the rocks after solidification. Such compression would certainly have brought about a much more uniform degree of foliation.

According to the writer's view, these variations are best explained as due to forced differential flowage in the pasty magmas, probably after partial consolidation. Regarding the origin of igneous rock foliation, Pirsson says: "Sometimes this texture has been imposed upon the igneous rocks after they had solidified, by intense pressure and shearing, and sometimes while they were still soft, pasty, and crystallizing, by forced differential flowage, due to various causes."[1] Those portions of the magma which were forced in probably a more fluid condition between other, probably more pasty or solidified, portions would have had a more perfectly developed foliated structure.

According to Leith: "Many more schists than gneisses have been proved to be the result of mashing of igneous rocks. . . . . In fact, so commonly do the igneous rocks appear when mashed to take on schistose as contrasted with gneissic structure as to raise the question whether gneisses are not exceptional results, most gneisses to be explained as igneous rocks with original flow structures."[2] The evidence from the Adirondacks is in harmony with

[1] L. V. Pirsson, *Rocks and Rock Minerals* (1908), p. 356.

[2] C. K. Leith, *Structural Geology* (1913), p. 103.

this statement by Leith, since anything like true schists are very rare if not wholly absent from the syenite-granite series.

Significance of granulation.—Granulation of the rocks of the syenite-granite series is of common occurrence. Most of the mineral constituents are more or less granulated, though it is quite the rule that the quartz shows the effects of crushing less than the others. In the greatest bulk of the rock the cataclastic texture shows itself by flattened or irregular lens-shaped quartz individuals, and more or less lens-shaped broken feldspars, imbedded in a mass of small broken feldspar grains together with some crushed quartz and leaves of mica. In many cases more or less thoroughly elongated and crushed hornblende or augite also occur.

This granulation has usually been regarded as proof that the rocks have been subjected to severe lateral compression and crushing after their consolidation. Thus Smyth, keeping in mind the frequent lack of crushing of the quartz, has said: "As the quartz could hardly flow while the feldspar fractured, the conclusion is obvious, and seems to be well grounded, that, in the case of the quartz, there has been crystallization after the production of cataclastic structure in the rock."[1] But does this prove the quartz to be largely recrystallized or of secondary origin? Could not movements in the magma during a late stage of consolidation, and before much quartz (the last to form) had crystallized out, have caused granulation of the earlier-formed crystals, while the quartz would have been more or less unaffected? In explaining the origin of foliation in the granite-gneiss of the Thousand Islands region, Cushing says: "The rock has been much crushed and somewhat recrystallized under compressive stress, since it originally congealed."[2] Now, while some granulation and recrystallization may have taken place after the magma consolidation, it is by no means a necessary inference that the granite has been much crushed and principally foliated after it had congealed. Strong evidence against severe compression of the Adirondack region has been presented in this paper, while the best evidence points to the origin of the foliation as essentially a flow structure developed under moderate

[1] C. H. Smyth, *15th Ann. Rep. New York State Geologist*, 1895, pp. 488–89.

[2] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 102.

pressure. This being the case, it is only necessary to consider that there were movements in the slowly cooling and stiffening magma whereby the minerals already crystallized out were more or less broken and drawn out into a sort of fluidal arrangement parallel to the foliation, while the minerals last to form were much less granulated. A significant point in this connection is that, in rocks which are definitely known to have been subjected to severe compression, quartz is quite generally more granulated than feldspar. Both Leith[1] and Loughlin[2] have emphasized this point. Now, in the Adirondack intrusives, as we have shown, the feldspar is very commonly distinctly more granulated than the quartz, and the evidence is, therefore, opposed to deformation of the Adirondack rocks by severe regional compression.

The facts that degree of foliation and granulation often vary markedly within a few feet or yards, and that the most perfectly foliated portions are often also the most highly granulated, are to be expected, because flowage in certain portions of the magma during the late stage of consolidation would produce in those portions not only good primary foliation but also notable crushing of the already formed minerals by the movements in the stiff, pasty magma. It seems impossible to explain satisfactorily such marked differences in degree of both foliation and granulation in the syenite-granite series except as the result of movements in the congealing magma. In few cases, if any, is there evidence for shearing, so that if compression of the region be assumed as the cause of the foliation and granulation, it is impossible to explain why adjacent zones often present such differences in degree of foliation and granulation.

Again, the general lack of notable granulation in the oldest rocks of the region—the Grenville—is not compatible with the idea of production of cataclastic structure in the intrusives by lateral pressure, else why were the still older rocks also not proportionately affected?

Other workers have presented strong evidence for the production of a granulated or protoclastic texture in igneous rocks by some

[1] C. K. Leith, *U.S. Geol. Surv., Bull. 239*, 1905, pp. 33–34.

[2] G. F. Loughlin, *ibid., Bull. 492*, 1912, p. 128.

such process as that outlined above. Barlow, describing the granite of central Ontario, says: "The movements . . . . continued as the rock cooled and while it was filled with abundant products of crystallization, the movements being brought to a close only by the complete solidification of the rock. Evidence of protoclastic structure can, therefore, be seen throughout all the areas colored as granite or granite-gneiss on the map."[1]

Teall says, regarding the granite of the county of Kircudbright: "The quartz and alkali feldspar, which . . . . were the last constituents to solidify, are those which have yielded most to the deforming stresses. They show signs of crushing. . . . . It is probable that the pressure acted before the rock mass had actually cooled."[2]

McMahon, discussing the gneissic granite of the Himalayas, says: "It is no argument against the idea of the development of foliation before final consolidation of the granite to point to evidence of strain and mechanical action in the rock; for the existence of strain and mechanical action during the critical period in the history of the granite is an essential part of the theory itself."[3] He admits that the granite has been subjected to lateral pressure but says that this does not prove the foliation to have been produced by such pressure.

Weinschenk,[4] explaining certain schistose Alpine granites, suggests that, in a somewhat advanced stage of magma consolidation, a crystalline skeleton is formed whose interstices are filled with liquid magma. Movements cause crushing of the skeleton, breaking the feldspars and bending the mica plates. Quartz, the last mineral to crystallize, is flattened out but not much broken.

According to Trueman: "It seems not illogical to assume that the movements which were, apparently, present late in the period of consolidation should have sometimes been continued after portions or the whole of the rock had completely solidified. If such

[1] A. E. Barlow, *Geol. Surv. Can., Mem. 57*, 1915, p. 48.

[2] J. J. H. Teall, *Mem. Geol. Surv. Great Britain, Expl. Sheet 5*, 1896, p. 43.

[3] C. A. McMahon, *Geol. Mag.*, N.S., Decade 4, IV (1897), 347.

[4] E. Weinschenk, *Congrès géol. inter., Compte rendu*, Session VIII, 1 (1900), 341.

were the case there would result considerable recrystallization and granulation so that typical crystalloblastic or cataclastic textures might be superimposed upon that resulting from primary consolidation."[1]

The possibility of some granulation and recrystallization in the Adirondack intrusives after complete consolidation is admitted by the writer, but, in view of the evidence above presented, such processes must have had relatively little to do with the development of the textural and structural features of the rocks.

Cause of mineral elongation.—Still another matter to consider briefly is the cause of the flattening or elongation of minerals in the primary gneiss. Flattening or elongation of minerals, especially quartz and feldspar, are common in the Adirondack intrusives, varying from rocks in which the phenomenon is scarcely noticeable to others in which it is extremely developed. It is the writer's experience that many such variations exist within short distances. Quartz exhibits such flattening better and more frequently than the feldspars. The writer believes that the mineral flattening or elongation was caused essentially by crystallization in the magma under pressure. Trueman[2] has recently presented considerable evidence to show that elongation (and presumably flattening) of mineral constituents by crystallization under differential pressure must often have been a very important factor in the production of foliation of primary gneisses.

In the Adirondack syenite-granite series, quartz shows the effects of flattening most because it was the last mineral to crystallize out and hence was not subject to so many of the movements in the magmas. Loughlin presents a similar argument regarding the Sterling granite-gneiss of Connecticut as follows: "After crystallization had become so far advanced that the rock became a mass of feldspar crystals (plus a small amount of quartz) with interstices filled with still fluid quartz, the feldspars would suffer strain, rotation, and slicing, and become a more or less granular lens-shaped aggregate elongated in the direction of least pressure. . . . . As the interstitial quartz began to crystallize, it would be

[1] J. D. Trueman, *Jour. Geol.*, XX (1912), 244.

[2] *Ibid.*, XX (1912), 235–42.

obliged to take on the form of the elongated or flattened interstices."[1]

It is not at all necessary to assume a very active lateral compression of the region to account for this pressure. As suggested by Cushing,[2] considerable compression of the magmas must have resulted from the batholithic intrusions, which, in order to make room for themselves, exerted a shouldering pressure upon the adjacent rocks. It is believed that such a shouldering pressure within the magmas was sufficient, not only to cause more or less flattening and elongation of minerals during consolidation and crystallization, but also to determine to a considerable extent the directions of the magmatic currents and hence the resulting strike of the foliation. Under the very conditions of intrusion, differential pressures must have been common, thus best explaining the frequent variations in degree of flattening of mineral constituents. This view does not of course preclude the possibility of moderate lateral pressure exerted throughout the whole region during, or even after, the magma consolidation.

Foliation of batholithic borders.—Before leaving this discussion another feature of the foliation of the intrusive masses should be mentioned, namely, that they often exhibit a greater degree of foliation and granulation around their borders than in their interiors. This phenomenon seems to be best shown in the anorthosite and the gabbro, and will be discussed below. Suffice it to say here that production of foliation and granulation in the congealing magmas affords a more plausible explanation for the peripheral distribution of such features than their production by compression of the whole region.

Summary.—During the process of intrusion, which was long continued, the great syenite-granite magmatic masses were under only enough lateral pressure to control the general strike of the uprising magmas with consequent tendency toward parallel arrangement of syenite-granite and invaded Grenville masses; the foliation is essentially a flow structure produced under moderate pressure during the intrusion; the sharp variations of strike on large and

[1] G. F. Loughlin, *U.S. Geol. Surv., Bull. 492*, 1912, p. 129.

[2] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 101.

small scales, and rapid variations in degree of foliation, are essentially the result of varying magmatic currents under differential pressure, principally during a late stage of magma consolidation; the almost universal, but varied, granulation of these rocks was produced mostly by movements in the partially solidified magma, and possibly in part by moderate pressure applied after complete consolidation; and the mineral flattening or elongation was caused by crystallization under differential pressure in the cooling magma.

FOLIATION OF THE ANORTHOSITE

It is not the present purpose to discuss thoroughly the origin of the structural and textural features of the Adirondack anorthosite. Only a few of the more important phenomena will be briefly considered. In general, the explanations above given regarding the foliation and granulation of the syenite-granite series apply also to the anorthosite.

Character of the anorthosite.—With the exception of a few small outlying masses, the anorthosite occupies a practically unbroken area of 1,200 square miles in the central-eastern Adirondack region. It quite certainly represents a single great intrusive body which is older than the syenite-granite series. In its typical development the rock consists almost wholly of basic bluish-gray plagioclase and is very coarse-grained, the feldspars often measuring from one to several inches in length. There are several important differentiation variations of the great mass. One of these is coarse-grained, but carries a considerable percentage of dark minerals; another is finer-grained and more gabbroic looking, owing to dark minerals, chiefly augite and ilmenite; while still another facies consists almost wholly of white basic plagioclase, or such white feldspar and more or less dark minerals. The great bulk of the rock is highly feldspathic and practically devoid of foliated structure, probably partly because of lack of minerals favorable for its production or accentuation, while the more gabbroic (especially finer-grained) types are almost invariably well foliated, frequently excessively so.

All of the varieties show more or less granulation, sometimes to a high degree, this being particularly true of the less coarse-

grained gabbroic types. As regards amount of granulation of feldspar, it is probably not very different in anorthosite and syenite-granite. The gabbroic, well-foliated, and granulated facies are developed on a grand scale around the borders of the great anorthosite area, but similar types are often encountered irregularly distributed throughout the area. Large feldspar individuals, usually unaltered rounded or lens-like cores of crystals, quite typically stand out prominently in a finer-grained, generally well-granulated, groundmass. In spite of much granulation, it seems certain that the typical original rock (before thorough consolidation) was characterized by a coarse porphyritic texture.

Cause of the foliation and granulation.—The foliation and granulation of the anorthosite has been explained as due to the same severe compression of the region which is supposed to have caused similar phenomena in the syenite-granite series. According to this view, the more general lack of anorthosite foliation is considered to be due to lesser effect of the regional pressure toward the interior of the great intrusive body than around its borders. Also it is thought that coarseness of original grain and general lack of minerals, especially dark minerals, other than feldspar have militated against such complete granulation and foliation of the rock as characterizes the syenite-granite series.

Regarding severe compression after the magma consolidation as the prime cause of the foliation and granulation is, however, open to many of the same objections already discussed in connection with the syenite-granite series. It is the writer's belief that an insurmountable objection to the severe-compression idea lies in the fact that there are so many sudden variations in degree of foliation and granulation, and in strike of foliation, throughout the great anorthosite area. Thus, well within the area, the writer has repeatedly seen very gneissoid gabbroic facies—both coarse and medium-grained—in close proximity to gabbroic facies of similar grain with little or no foliation. All types of anorthosite also often exhibit varying degrees of granulation in close proximity. If they were caused by regional compression, why are so many portions highly foliated or granulated when others close by are unaffected? Also, if regional compression were the cause of the foliation, how are

the frequent very notable variations in strike, often within relatively small areas, to be accounted for?

According to the general principles outlined in connection with the foregoing discussion of the syenite-granite series, it is the writer's conception that the foliation and granulation of the anorthosite were developed essentially by flowage or other movements in the magma under moderate pressure, mostly just prior to its complete consolidation. As Cushing has said regarding the Long Lake quadrangle anorthosite: "In some portions of the rock the feldspar crystals are more numerous, are smaller and are all arranged with their long axes parallel. This is a 'flow structure' due to movements in the mass during solidification."[1] The better foliated or better granulated belts throughout the great mass represent merely places where the magmatic currents or other movements were more pronounced. The coarser-grained portions would of course have undergone less complete granulation, but coarseness of grain and absence of dark minerals would not necessarily have tended to prevent the development of foliation. Thus, in the Broadalbin, North Creek, and Lake Pleasant quadrangles the writer has observed coarse granite-porphyry, almost free from dark minerals, with highly gneissoid structure due to thorough flattening out of both quartz and feldspar, while in other cases the porphyry shows little or no foliation. It would seem, therefore, that the general absence of foliation throughout so much of the anorthosite is best explained as the result of the much more uniform intrusion of this single great body which is less involved with Grenville masses, or, in other words, to much less forced differential flowage. Because of its great size, the pressure due to shouldering effect on adjacent rocks would be relatively slighter toward the interior of the mass.

Not only is the foliation well developed around the margin of the great intrusive, but it also appears to be especially well exhibited in many parts of the area in the gabbroic facies where they are close to masses or inclusions of Grenville. Just as flow structure is often best shown close to the wall-rock of, or an inclusion in, a small intrusive body, probably because of friction against the wall-rock

[1] H. P. Cushing, *New York State Mus. Bull.*, No. 115, 1907, p. 472.

or inclusion and consequent development of differential pressure and flowage, so, on a large scale, in the anorthosite body it is reasonable to think that foliation due to magmatic flowage would have been best developed around the margin of, or close to, masses of country rock within the great anorthosite body. In many other places, however, primary gneissoid structures may have been produced by differential flowage far from any country rock.

The cataclastic texture of the anorthosite is believed to have resulted from the crushing of minerals already crystallized out of the stiff, solidifying magma by movements in the magma. The shouldering pressure exerted by the great intrusive mass in order to make room for itself must have been sufficient to have affected the whole mass until final consolidation.

Kemp says, regarding the anorthosite of the Elizabethtown quadrangle: "The entire area has been subjected to such severe pressure and granulation that the outer borders of the crystals are always crushed to a finely granular and whitish mass. Within this rim the bluish nuclei of the plagioclases remain. When shearing and dragging have been added the nuclei yield augen-gneisses."[1] It is, however, not at all necessary to assume severe regional pressure to account for these phenomena. Forced differential flowage in the stiff, nearly congealed magma (under pressure due chiefly to its own shouldering action) could have produced most, if not all, of the granulation and dragging effects, the "augen" being cores of what were large, probably porphyritic, feldspars in the nearly solidified magma. Moderate pressure during or even after consolidation may possibly have operated to accentuate the phenomena.

Adams says, concerning the Morin anorthosite north of Montreal: "The circumstance that the streaks or irregular bands (foliation), when present in the otherwise massive rock, assume no definite direction, but twist about as if owing to movements of the rock while in a pasty condition, indicate that they have been produced by movements before the rock solidified. . . . . The granulation of the coarsely crystalline massive anorthosite, usually with concomitant development of more or less foliated or schistose structure in the way described, is undoubtedly due to movements

[1] J. F. Kemp, *New York State Mus. Bull.*, No. 138, 1910, p. 28.

in the rock, resulting from pressure which acted subsequent to or possibly during the last stages of its consolidation."[1]

FOLIATION OF THE GABBRO

The gabbro here considered is the latest Adirondack intrusive which exhibits foliation and granulation. Diabase is the only intrusive still younger. A few years ago the writer[2] discussed the origin of certain primary variations of Adirondack gabbro. At that time, in accordance with the usual idea, the foliation was thought to be largely a secondary structure and so was omitted from the discussion.

Character of the gabbro.—Most of the gabbro is in the form of small stocks or bosses, the outcropping areas typically ranging from elliptical to almost circular, and the dimensions from a few rods to one or two miles. They are especially well-shown on the North Creek, Long Lake, Elizabethtown, and forthcoming Blue Mountain geologic maps. Most of them are of pluglike or pipelike form, with practically vertical, sharp contacts against the country rock. The stocks exhibit many variations in composition and texture from the normal, homogeneous, dark, basic gabbro with diabasic texture, to lighter-colored rocks of dioritic and even syenitic make-up. They also range from fine-grained to very coarse-grained with feldspars up to an inch or more in length. The typical gabbro contains principally basic plagioclase, pyroxene, hornblende, biotite, garnet, and ilmenite, while orthoclase and quartz often occur in the more acidic facies.

A very important feature, from the standpoint of our present discussion, is the almost universal development of highly foliated amphibolitic borders which often completely surround the stocks, while the interior portions of the typical stocks are usually nonfoliated. In many cases, however, stocks seem to be wholly changed to amphibolite, or only very small cores remain. In still other cases coarse-grained gabbro shows gneissoid structure thoroughly developed throughout. As a rule the gabbro exhibits as good, if not better, foliation than the older intrusives. Often

[1] F. D. Adams, *Geol. Surv. Can., Guide Book No. 3*, 1913, p. 17.

[2] W. J. Miller, *Jour. Geol.*, XXI (1913), 160–80.

the degree of foliation varies much even well within single stocks.

Another very persistent feature is granulation which appears to be of two types, that of so-called "corrosion rims" around certain minerals, and a more generally distributed granulation. Granulated "corrosion rims" occur even in non-foliated gabbro with diabasic texture.

Cause of foliation and granulation.—The foliation and granulation of the gabbro, like that of the older intrusives, are quite generally regarded as secondary features brought about by the influence of regional pressure, the non-foliated, uncrushed cores of stocks being considered as portions protected from pressure influence. Granting the existence of regional compression severe enough to give rise to these phenomena, it is evident that the same pressure must have affected the older intrusives in a similar manner, but this we have proved to be not the case. It is very difficult to imagine a process of development of foliation, which boxes the compass around the borders of the gabbro stocks, by regional compression. Such foliation of course often strikes directly across the foliation of the older adjacent rocks, an excellent case in point being at the south end of the large stock just north of Loon Lake of the North Creek sheet. How can such phenomena be explained as due to regional pressure when it is well known that cleavage or foliation produced by this means must everywhere strike at least approximately at right angles to the direction of application of pressure? Also how are such frequent notable variations in foliation and granulation, not only in near-by stocks but also within stocks, to be explained?

According to the thesis of this paper, the foliation and granulation are largely, if not wholly, primary features. There are, admittedly, some puzzling things about the foliation and granulation of the gabbro, but certainly they are to be much more reasonably interpreted as caused by movements in the magma before complete consolidation.

Weinschenk, in explaining schistose peripheral zones around certain Alpine granitic cores, has suggested: "The consolidation of the rock commenced with the separation of the dark minerals—

biotite and hornblende. Mica formed first in the liquid mass. At this time the orogenic pressure acted upon the peripheral zone of the magma by orienting this mineral normal to the pressure. In the heart of the viscous mass this faculty of orientation was replaced by an interior tension not directed in any particular way."[1] Orogenic pressure did not exist in the Adirondack region, but if for it we substitute the pressures within the stock magmas themselves, this idea of Weinschenk affords a plausible explanation of the foliated borders. Considerable pressures must have obtained within the stock magmas which were intruded under very deep-seated conditions. Such pressure against the country rock, combined with the usual development of differential flowage in the magmatic borders, as already explained in this paper, would readily account for the peripheral foliated zones which were produced, no doubt, during a late stage of magma consolidation. But the conditions for magmatic pressure and flowage must often have varied a great deal, so that it is to be expected that, in some cases, even coarse-grained gabbro would exhibit primary foliation, while, in other cases, amphibolite would make up the whole mass, or, in still other cases, finer-grained, very gneissoid, and granulated belts or bands would occur in the midst of coarser, less foliated types. It should be noted in this connection that unmistakable flow structures do often occur around inclusions in the gabbro.

Applying these ideas, the puzzling features of various gabbro stocks find a ready interpretation. A good example is the stock near Blackbridge in the Lake Pleasant quadrangle.[2] For most part this is a very basic, gabbroic-looking rock, sometimes pretty massive and very coarse-grained, and at other times not so coarse, but streaked or almost banded, owing to layers of amphibolite. All phases of the rock are much granulated and distinctly gneissoid, the coarser-grained portions being least so. A diabasic texture frequently occurs. Differential flowage and other movements under pressure in the congealing magma best explain these phenomena. The more foliated, finer-grained belts in the midst of the

[1] E. Weinschenk, *Congrès géol. inter., Compte rendu*, Session VIII, 1 (1900), 340. Freely translated from the French.

[2] W. J. Miller, *New York State Mus. Bull.*, No. 182, 1916, p. 29–30.

coarser, less foliated rock may be readily interpreted as the result of a forcing of slightly more liquid portions of the congealing magma through more solidified portions.

Highly developed "corrosion rims" are beautifully and extensively developed in the Adirondack gabbros.[1] Their occurrence even in non-foliated gabbro with diabasic texture argues strongly for their production before final consolidation of the magma, this possibility having been recognized by other investigators. How could regional compression have caused so much of this sort of granulation without otherwise affecting the rock? Also, if granulation of this sort has resulted from movements prior to solidification of the magma, why could not the more general cataclastic textures of the syenite-granite, anorthosite, and gabbro have been similarly produced? As in the older intrusives, so in the gabbro, the finer-grained more foliated portions are quite generally the most granulated, this doubtless resulting from more pronounced flowage movements in certain portions of the magma late in the process of consolidation.

[1] W. J. Miller, *Jour. Geol.*, XXI (1913), 168–70.

THE COMPOSITION OF THE AVERAGE IGNEOUS ROCK[1]

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The composition of the "average igneous rock" has been computed by Clarke, Harker, and Washington. Clarke's most recent estimate was published in 1915.[2] The earlier computations were made by averaging the results of large numbers of analyses, and the later by averaging each constituent according to the number of determinations made, and reducing the sum to 100 per cent. The objection to these methods, as is well known, is that they take no direct account of the quantitative distribution of the rocks; each analysis or determination receives the same weight, regardless of the size of the geologic body that it is held to represent. The force of this objection has been recognized by Clarke,[3] who concludes that "the whole land surface of the earth must be taken into account before the true average can be finally ascertained."

A first approximation to this true average can be reached by calculations based on data recently assembled by Daly in *Igneous Rocks and Their Origin*. In Table IV is given the total areas covered by each of the rock species named and mapped in the Cordilleran and Appalachian folios of the United States Geological Survey. The area occupied by any rock species divided by the total area of igneous rocks (16,728 square miles) gives a weight-factor, and this factor multiplied by the average composi-

[1] Published with the permission of the Director of the U. S. Geological Survey.

[2] *Analyses of Rocks and Minerals from the Laboratory of the United States Geological Survey*, U.S. Geological Survey Bulletin, No. 591, pp. 18–22, 1915.

[3] *The Data of Geochemistry* (3d ed.), U.S. Geological Survey Bulletin, No. 616, p. 26, 1916.

tion of the species, which has been computed by Daly in Table II, gives the percentage contribution of that species to the composition of the average igneous rock. In this calculation species covering less than 2 square miles were omitted, as their inclusion would not affect the second decimal place of the result. The composition thus calculated is that of the average exposed igneous rock; whether it represents the composition of the average igneous rock of the 10-mile crust depends on the verity of certain petrogenic considerations.

The following proportional factors were used in the computations:

Granite, including allied porphyries	0.23212
Granodiorite	.12195
Rhyolite	.12834
Andesite	.23864
Basalt	.20773
Quartz monzonite and allied porphyry	.00108
Diorite	.01802
Gabbro	.02225
Anorthosite	.00311
Syenite and syenite porphyry	.00389
Monzonite	.00161
Nepheline syenite	.00024
Shonkinite	.00054
Theralite	.00036
Peridotite	.00436
Pyroxenite	.00011
Diabase	.01602
Dacite	.00536
Trachyte	.00036
Latite	.00030
Phonolite	.00048
Nepheline melilite basalt	.00018
Limburgite	.00012
Total	1.00000

The result of the new calculation of the composition of the average igneous rock is given in column I of the accompanying table; for comparison, the most recent estimate by Clarke is given in column II.

Notwithstanding the widely different methods employed in the calculations the new estimate agrees to a remarkable extent with

COMPOSITION OF THE "AVERAGE IGNEOUS ROCK"

	I	II
SiO_2	61.64	60.47
TiO_2	0.73	0.80
Al_2O_3	15.71	15.07
Fe_2O_3	2.91	2.68
FeO	3.25	3.50
MnO	0.16	0.10
MgO	2.97	3.85
CaO	5.06	4.88
Na_2O	3.40	3.41
K_2O	2.65	3.03
H_2O—	1.26	0.48
H_2O+		1.44
P_2O_5	0.26	0.29
	100.00	100.00

Clarke's average. The most notable departures are the increase in silica and the relatively strong decreases in magnesia and potassa.

Reviews

The General Magnetic Survey of the Earth. By L. A. Bauer. Bull. Am. Geog. Soc., XLVI, July, 1914, pp. 481–99. Figs. 6.

About the earth sphere are lines of magnetic force very similar to those of any magnetic field, their poles not quite coincident with those of the earth axis. That the magnetic needle varies from true north was discovered at least as early as the fifteenth century, when Columbus sailed west from Europe. Subsequent observations have shown in addition that there is a constant change in the earth's magnetism, making repeated magnetic surveys necessary. In magnetic observations, the horizontal declination, vertical magnetic dip, and intensity of the attraction are measured. Since 1904 the Carnegie Institution of Washington has conducted extensive magnetic surveys of the earth in which a total mileage of approximately one million miles has been traveled. Ocean surveys have been conducted in a specially constructed non-magnetic vessel.

R. C. M.

The Mud Lumps at the Mouths of the Mississippi. By Eugene W. Shaw. U.S. Geol. Surv., Prof. Paper 85, Part B, 1913. Pp. 17, pls. 3, figs. 6.

The territory within a mile or two of each of the mouths of the Mississippi is characterized by large swellings or upheavals of tough bluish-gray clay, to which the name "mud lumps" has been applied. Many of the mud lumps rise just off-shore and form islands having a surface extent of an acre or more and a height of 5 to 10 feet, but some do not reach the water surface. Almost all occur near the bars at the mouths of the rivers. In contrast with the general structure of the delta, which is composed of thin, alternating sandy and clayey beds, the mud lumps are of thick, compact clay. On and around the clay core lies a series of faulted and folded strata of sand and silt which have been carried up from the sea bottom and deformed in the upheaval. It seems most likely that these lumps owe their origin to a squeezing of the soft layers, and an accumulation of clay from such layers in places where the pressure is less strong. This postulates a gentle seaward flow of layers

of semifluid clay, the flow meeting resistance particularly at the ends of the Passes, where there is an accumulation of more resistant material and a greater lack of equilibrium between the heavy land on one side and the water on the other. The report is somewhat preliminary in nature.

R. C. M.

The Upper Cretaceous and Eocene Floras of South Carolina and Georgia. By E. W. BERRY. U.S. Geol. Surv., Prof. Paper 84, 1914. Pp. 200, pls. 29, figs. 12.

The Upper Cretaceous of South Carolina is represented by the Black Creek formation, which is divisible into two members, the Middendorf arkose, with certain related clays, and a sandy, marine member. A number of localities in the Middendorf have yielded plant remains, among which are found magnolias, figs, laurels, oaks, walnuts, cinnamon, the eucalyptus, etc. The collection numbers 75 species. The climate, indicated by the types present, is subtropic, or at least mild temperate, for with little variation the flora extends to the western coast of Greenland.

The Upper Cretaceous of Georgia, the flora of which is described in the second part of the paper, is confined to a triangular area lying west of the Ocmulgee River and comprises the eastward extension of the Eutaw and Ripley formations. The former contains an abundant fossil flora in its lower division, but the latter, except in the upper part, contains little plant life. The physical conditions suggested are in accord with the evidence from South Carolina and point to a mild, humid climate, without frosts.

A small but very interesting Middle Eocene flora from Georgia is described in the third division of the paper. The Middle Eocene of Georgia is for the greater part deeply buried beneath younger sediments, but in the area lying between the Ocmulgee and Savannah rivers there are outcrops which have yielded a fossil flora of 17 species. Most of these have not been described previously and the author compares them with European Eocene and modern related types. The conclusion is reached that the Middle Eocene of this region enjoyed a much more tropical climate than is represented by any other known Eocene flora. The Georgia flora was probably immigrant from the south and reached northward at least as far as latitude 33° N.

R. C. M.